A METHODOLOGY FOR REPRESENTING LOW AND ZERO CARBON TECHNOLOGIES IN HOME ENERGY RATINGS

by

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ABSTRACT

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Home Energy Ratings (HERs) have been a factor in reducing emissions from UK housing stock over the last twenty years. The new EU Energy Performance of Buildings Directive requires the contribution from Low and Zero Carbon Technologies (LZCs) to be included in such ratings. However, LZCs do not behave in the same way as fossil-fuelled energy sources and the requirement raises several questions about the existing philosophy of energy ratings. This thesis aims to answer these questions in a practical way by developing and testing solutions as a basis for a new methodology for assessing examples of LZC output in the UK's NHER, to permit straightforward comparison and quantification of the merits of each technology.

The example technologies of solar domestic water heating, photovoltaic cells and micro-combined heat and power were chosen to illustrate the scope for comparison within a HER in terms of location, demand matching, and export, from amongst the technologies likely to be in general use in future. Hourly models of these LZCs have been investigated, selected and adapted for use in the energy model underlying the HER, then simplified to a format appropriate for

use in a HER, preserving the most important details. The results of this simplification exercise were to give the variables that most influence the performance of each chosen LZC technology. In each case, variables dependant upon location were amongst those that had the most significant effect on yield.

It is desirable to use different criteria when rating renewable energy than with fossil energy. Where cost and quantity of fuel used are the main issues in rating conventional technologies, demand matching and the emissions reduction potential of export are major concerns in rating LZCs, so to approximate these external factors, selected historical data describing national profiles of electricity demand and generation mix have been adapted for use with the LZC models alongside generated domestic electricity demand profiles. These have been used in evaluating the worth of replacement energy as it changes over time.

The profile of yield and export for each LZC type and combination can be compared to the domestic demand and national demand profiles respectively. For each of these comparisons, a factor describing the fit of each supply profile to the demand has been derived. These factors have been applied along with multiple regression analysis in simplifications of the models. Equations have been derived which best capture the expected energy performance of the LZC types for all ordinary situations, and are appropriate for use in HERs.

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ABBREVIATIONS

μ-CHP	Micro Combined Heat and Power
APX	Amsterdam Power Exchange
BM	Balancing Mechanism
BRE	Building Research Establishment
BREDEM	Building Research Establishment Domestic Energy Model
CO_2	Carbon Dioxide
DEM	Domestic Energy Model
DSP	Detailed Simulation Program
EEX	European Energy Exchange
EHCS	English House Condition Survey
EPBD	Energy Performance of Buildings Directive
HER	Home Energy Rating
LCA	Life Cycle Analysis
LZC	Low or Zero Carbon Technology
MPPT	Maximum Power Point Tracking
NES	National Energy Services
NETA	New Electricity Trading Arrangements
NHER	National Home Energy Rating
PIC	Programmable Intelligent Controller
PV	Photovoltaic
SAP	Standard Assessment Procedure
SDWH	Solar Domestic Water Heating
SOFC	Solid Oxide Fuel Cell
SRCC	Solar Rating and Certification Corporation
TRY	Test Reference Year
UNFCCC	United Nations Framework Convention on Climate Change
VIF	Variance Inflationary Factor

NOMENCLATURE

A'	Effective Collector Aperture Area	m^2
A_{Array}	Array Area	m^2
A_c	Collector Area	m^2
A_{module}	Module Area	m^2
A_{sp}	Solar Panel Area	m^2
Cp	Heat Capacity of the Working Fluid	J/kg/K
$Demand_{Day,Min}$	Electrical Demand for the Minute of the Day	W
E_{Annual}	Annual Electrical Export	kWh
Ei	Monthly Average Array Electricity Output for Time Step i	kWh
F_R	Collector Heat Removal Factor	%
F_{sp}	Collector Panel Efficiency	%
G_B	Incidental Gains	W
$Gen_{Day,Min}$	Electrical Generation from the Unit for the Minute of the Day	W
G_T	Reference Irradiation	W/m^2
G_{tilt}	Annual Mean Daily Peak Irradiance	MJ/m^2
h_e	Efficiency of Power Conditioning Equipment	%
h_i	Average Efficiency for Time Step i	%
$h_{mp, ref}$	Maximum Power Point Efficiency at Reference Temperature	%
$h_{mp, ref}$	maximum power point efficiency at reference temperature	%
H_{tilt}	Annual Mean Daily Irradiation	MJ/m^2
I_{mp}	Current at the Maximum Power Point	A
I_o	Monthly Average Extraterrestrial Irradiation	MJ
I_T	Incident Irradiation on the Tilted Surface	MJ
k_T	Clearness Index	
kWi	Output of the Array for Time Step i	kW
kW_{YF}	Output of the Array Assuming Inverter Saturation	kW

L	Daily Mean Load	J
Li	Average Load for the Hour	W
LR	Load Ratio	
m	Average Mass of Water Moved Through the Collector	kg/second
$P_{CONSUMPTION}$	Electricity Demand	kWh
P_{inv}	Rated Inverter Power	kW
$P_{PV,STC}$	Rated Power of the Array at Standard Test Conditions	kW
PV_{USE}	PV Generation	kWh
Q_h	Heating Input	W
Q_t	Tank Loss Rate	W
Q_u	Hot Water Demand	W
R^2_j	Coefficient of Multiple Determination of Xj with all other X Variables	
R_b	Ratio of Beam Irradiation on Array to Horizontal	
S	Incident Irradiation	J
S_{30}	Radiation Falling on South Facing 30° Inclined Plane	W/m²
$Size_{System}$	System Sizing	%
T_a	Annual Mean Daytime Air Temperature	°C
$T_{a,i}$	Ambient Temperature for Time Span i	°C
T_a'	Ambient Temperature in the Room in which Storage Tank is Situated	°C
T_c	Annual Mean Cold Water Supply Temperature	°C
T_{LR}	Mains Water Temperature	°C
T_{ref}	Cell Specification Reference Temperature	°C
T_s	Store Temperature	°C
t_{sp}	Set Point Temperature	°C
U	Collector Heat Loss Coefficient	W/m²K
UA_s	Storage Tank Loss Coefficient Area	W
U_B	Dwelling Specific Loss	W/K
U_L	Collector Loss Coefficient	%/°C
U_L	Cell Loss Coefficient	%/°C

UT	Useful Total	%
V	Daily Mean Hot Water Requirement	L
VIFj	Variance Inflationary Factor for Variable j	
V_{mp}	Maximum Power Point Voltage	V
V_s	Preheat Storage Vessel Volume	L
X_c	Critical Radiation Level for Hour	
YF_i	AC Yield Factor	%
Z_i	Correction Factor for Irradiation Angle	
β	Tilt Angle	°
ε_L	Heat Exchanger Effectiveness	%
η_0	Zero Temperature Loss Collector Efficiency	%
μ_{mp}	Maximum Power Point Temperature Coefficient	%/°C
$\mu_{P, mp}$	Maximum Power Point Efficiency Temperature Coefficient	%/°C
μ_{VOC}	Temperature Coefficient of Open Circuit Voltage	mV/°C
ϱ	Ground Reflectivity	%
$\tau\alpha$	Transmittance Absorptance Product of Cells	

CHAPTER 1: THE NEED FOR REPRESENTATION OF MICROGENERATION TECHNOLOGIES IN HOME ENERGY RATINGS

1.1 Global Warming and Energy Efficiency

The issue of energy efficiency is rising on the political agenda of many nations of the world. Concerns of environment, sustainability, and national energy independence guide the movement towards more economical use of the Earth's resources. It is difficult to measure humanity's overall use of materials and energy but credible estimates state that it currently stands at 20% more than the natural capacity of the Earth (Wackeragnel et al., 2002). There is a strong argument for a more sustainable approach to development, and a move away from the consumption of fossil fuels for energy.

Amongst the gas emissions arising from use of fossil fuels, Carbon Dioxide (CO_2) may be the most problematic. There is growing scientific consensus that the surface temperature of the Earth has been rising over the past one hundred years (IPCC, 2001), with belief that gas emissions (particularly CO_2) resulting from human activities are the reason (Figure 1.1). This process has become known as global warming, and the gasses believed to cause it are referred to as greenhouse gasses. The conviction in global warming has led to reports and subsequently international agreements struck to abate greenhouse gas emissions[1] and to protect the environment. These agreements require action on the international, national, and local level to reduce emissions of carbon from fossil fuels.

[1] Greenhouse gas emissions are commonly referred to as 'carbon' emissions. This acknowledges the major importance of CO_2 in the global warming effect but also considers the potential of the other gasses.

There remains dissent as to whether the global warming phenomenon exists, and whether it is due solely to human activities e.g. (Lomborg, 2001) (McIntyre & McKitrick, 2003), or for natural reasons. However, concerns for security of fuel supply alone are sufficient to justify greater care over use of fossil fuels. This is the philosophy used in the international agreements: the measures for limiting carbon emissions should also be financially advantageous for the countries that implement them.

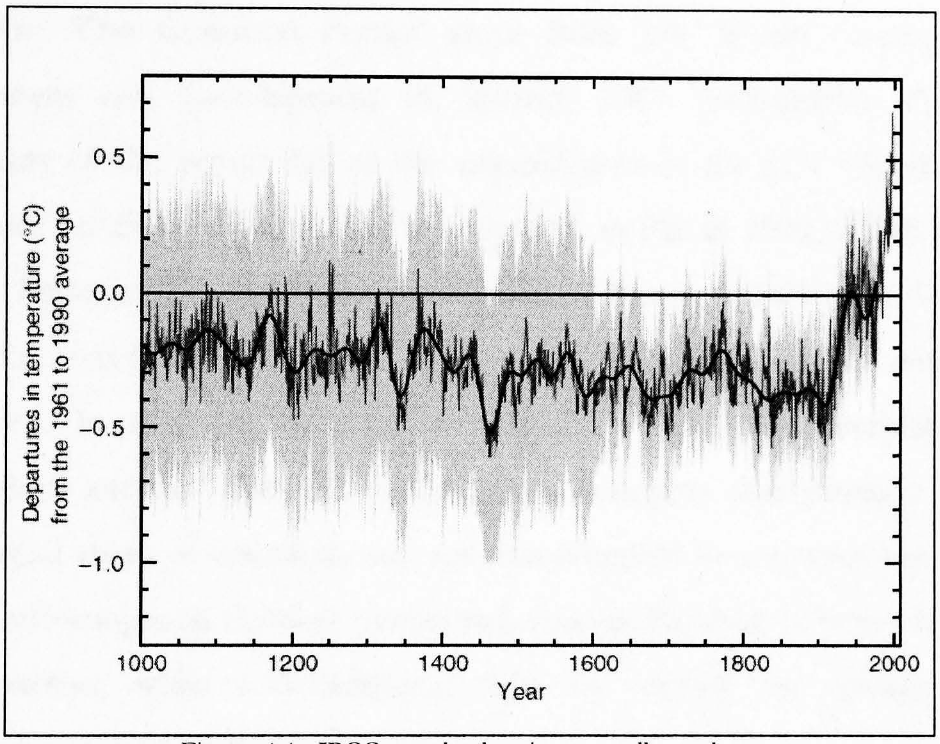


Figure 1.1: IPCC graph showing overall northern hemisphere temperature over the last 1000 years, relative to 1990 (IPCC, 2001)

1.2 International Agreements

International agreements on limitation of carbon emissions have been slow to emerge. The first report recommending changes to production and consumption of energy was fifteen years before the first legally binding international agreement on abatement of carbon emissions came into force. Successive agreements have defined the global warming problem, the means to address it, and created a legal framework starting on the path to emissions reduction. The aims of these agreements have been taken up in EU and UK legislation directly utilising rating schemes in the move towards energy efficiency in the home. The concept of overall reduction in carbon emissions through trade-off of emissions levels in different countries is a parallel to a common rating philosophy of trading the energy efficiency of building components to achieve a particular overall standard for the dwelling.

1.2.1 *The Brundtland Report*

The report 'Our Common Future' arose from The World Commission on Environment and Development in Madrid, 1987 (Brundtland, 1987). The conclusions of the report led to the organisation of the UN United Nations Conference on Environment and Development in Rio in 1992, which produced the UN Framework Convention on Climate Change (UNFCCC) (UNFCCC, 1992). This convention was a voluntary agreement to reduce carbon emissions to 1990 levels. It proposed the idea of trading of emissions potential between industrialised nations. This means that those countries that produce less than their allotted share of emissions can sell this potential to countries that produce more. It encourages an absolute overall reduction in the level of emissions among the signatories, while acknowledging that the capacity to change national infrastructure quickly is limited.

1.2.2 *The Kyoto Protocol*

The Kyoto Protocol (Kyoto, 1997) was the first legally binding international initiative for the abatement of carbon emissions. It followed from the UNFCCC, and came into force on 16th February 2005. It gave specific emissions reduction targets for countries based upon their economic development. As with the UNFCCC, it allows for trading of carbon emissions between nations. Countries with less industrial development and more forested areas can sell their reduced CO_2 emissions to those that pollute more. Many countries are now expected to fail to meet their target emissions reduction for 2010 under the agreement (EEA, 2004).

The European Union collectively ratified the Kyoto protocol on 31st May 2002 (UN, 2002). Member states were required to implement strategies to reduce their carbon emissions to the amount they emitted in 1990, by the year 2010. The Kyoto protocol allows countries to trade potential emissions between them to fulfil their obligations under the treaty. This is designed to encourage an overall reduction in emissions.

In accordance with the aims of the Kyoto protocol, the European Union has introduced the Energy Performance of Buildings Directive (EPBD) (EU, 2002) that requires programmes for improving buildings' energy efficiency to be implemented in member states. Energy ratings, both for commercial and for domestic buildings are a key part of the energy performance strategy.

Home Energy Ratings (HERs) can be a useful tool in enforcing energy efficiency in the domestic sector. A HER is a certification that a house achieves a certain level of energy efficiency. Additionally, it often gives a score to a home so that it can be compared like to like, and potential purchasers can estimate what their running costs will be for the year. It is also useful for putting energy efficiency on the agenda in a legislative context – a particular standard of efficiency can be specified with minimal scope for misinterpretation or evasion. A HER should be flexible enough to allow different ways to achieve a standard, reflecting the Kyoto protocol's philosophy of trading off varying emissions to achieve an overall target. The EPBD explicitly requires that energy performance standards be should consider electrical energy use for lights and appliances in buildings as well as heating costs. Moreover, it requires that energy ratings consider the contribution of Low and Zero Carbon Technologies (LZCs).

1.3 Home Energy Efficiency in the UK

The domestic sector accounts for 28% of energy use in the UK overall (DTI, 2005a) and 25% of all electricity use is in domestic lights and appliances. The UK's Climate Change Programme (HM Government, 2006) emphasises energy efficiency in building regulations and launches a number of home energy efficiency schemes.

In the UK, the government's commitment to the Kyoto protocol was emphasised by setting a target of 20% reduction in carbon emissions by the year 2010 - almost double the UK's required reduction of 12.5%. This was an ambitious undertaking, which needed stringent measures. Such measures have been applied to energy generation and industry. In the same manner that carbon emissions are traded internationally, UK companies can trade emissions potential between them (HMSO, 2002). Despite the commitment of the government, a 20% reduction in carbon emissions from 1990 now looks unlikely (DEFRA, 2005).

The UK government's commitment to supply energy from renewable sources, to stimulate the market for LZCs, and to provide secure energy supplies calls for a greater take-up of LZCs on the domestic market. This is particularly relevant given that historically, domestic take-up of LZCs has been low in the UK. The main restriction to take-up of LZCs in the domestic sector is the long payback time in relation to capital cost. Private sector homeowners move house regularly, and the payback times of LZCs, sometimes twenty years or more (DTI, 2001), are not realised in the average term of ownership. A LZC is not perceived by the public to be a significant improvement to the fabric of the house relative to the investment that is made in installing it. Solar domestic LZCs suffer a poor reputation, as it is believed that the UK does not have an appropriate climate for them (DTI, 2001). The solar domestic water heating industry has suffered from exaggerated vendor claims and poorly implemented system installations in the past. A focused exercise in building the reputation of LZCs and in reflecting their true cost and benefits could help bring the UKs utilisation of LZCs to the levels seen in continental Europe (Eurostat, 2002).

The UK's national emission reduction commitments in combination with EU legislation drive toward the incorporation of building integrated LZCs into its own national HER scheme. This could restore the reputation of these technologies and put them on the agenda when end users pursue a higher energy rating for a dwelling.

1.4 The Current Treatment of LZCs in UK HERs

HERs have been a major tool in promoting energy efficiency in the home over the last twenty years, and have become part of the legislative framework for improving building standards (ODPM, 2006). They are already widely used by many local authorities to evaluate the energy efficiency status of their housing stock and some have shown that this can be a useful tool in complying with government policy (Woking Council, 2003). If their scope is expanded to better reflect the performance of building integrated LZCs this may help to promote greater energy self-sufficiency in the domestic sector and to raise public consciousness of the value of LZCs.

Obviously, if local authorities could achieve increased contributions from LZCs in their domestic building stock this would help to meet the terms of the UK government's renewables obligation and support the development of a more positive attitude to sustainability. If homeowners and landlords are constructively encouraged to install LZCs in the home, at a cost becoming competitive with other energy efficiency improvements, and awareness of the increase the index of the HER based on a truer reflection of their carbon reduction potential, is fostered this should also encourages homebuilders to feature LZCs in their products. Additionally, vendors of LZCs need to differentiate their product from the competition and gain recognition for high construction standards.

It has been suggested that the two main UK HER schemes, the Standard Assessment Procedure (SAP) (BRE, 2006) and NHER based on the Building Research Establishment Domestic Energy Model (BREDEM) (Anderson, 1985), as yet represent LZCs incompletely and insufficiently well for all these objectives to be achieved (Baggett, personal communication, 2002). The reasons for this are expanded and the argument is developed and justified more fully in section 2.4. They are tested in relation to three important and representative LZC technologies in this thesis.

1.5 Aims of the Research

The main practical aim of this research was to show how three key LZCs, solar photovoltaics (PV), solar domestic water heating (SDWH) and micro-combined heat and power (μ-CHP) could be modelled within the Building Research Establishment Domestic Energy Model-12 (BREDEM-12) (Anderson, et al. 2002) to better reflect their potential, within the constraints imposed by the nature of the model and the conventions of its associated energy rating scheme. These constraints relate to the temporal granularity of the model and are fully described in section 2.6.

The overarching aim of the research was, through this improved representation, to provide schemes such as the NHER with the essential basis for changing their cost-based philosophy towards one that directly addresses climate change concern, perhaps through moving to a carbon based rating (Baggett, personal communication, 2002).

1.6 Outline of the Thesis

A review of the existing domestic energy models in the UK is given in Chapter 2. The adequacy of BREDEM-12 for integrated modelling of LZCs is discussed. Issues with the model are introduced, the resolution of which are detailed in later chapters. These include the irradiation model, dealing with seasonal differences in solar gains and temperature, the hot water and electricity demand models, and the requirement for a net metering solution. Chapter 2 also discusses the shortcomings of the current basis of UK HERs in energy price. It covers the argument for using alternative metrics such as carbon emissions as a basis for the index in HERs.

Chapter 3 addresses issues of solar radiation calculation, such as the appropriateness of horizontal irradiation data sources used and the consistency and accuracy of estimation of annual irradiation on a tilted surface. This is particularly important for solar domestic water heating and photovoltaic panels, which may sometimes be installed at non-optimum angles, and these effects are considered, comparing the current BREDEM-12 conventions with other methods that account for the proportion of diffuse radiation upon a tilted surface.

SDWH has great potential as a relatively inexpensive, low-tech renewable energy measure. It is well proven and is suitable for use in the UK climate. Chapter 4 explores the main configurations of SDWH installation for use in the model. Some simple design method techniques for predicting the solar fraction are compared with the existing BREDEM-12 approach. As the daily profile of hot water demand can be important in sizing a SDWH system the level of detail feasible in simplified models of this kind is considered. The assumptions made in order to simplify the chosen design method are explained.

In Chapter 5, the main elements of a PV installation are presented with discussion on how they are represented in simplified models, together with models for estimating irradiation and the electricity demand in the home. The potential of export of electricity to the grid as a major incentive for PV installers is considered, and it is shown why knowledge of the electricity demand through the day and the supply profile are important details in establishing the economic performance of a PV system. The typical design and costing method for a PV system is also described.

A number of issues relating to μ-CHP are discussed in Chapter 6. The principles of the technology are briefly discussed, focussing on the widely used Whispergen unit and the implications of electricity export and economic viability are explored. As export is dependent upon electricity demand and heating demand within the dwelling and the behaviour μ-CHP units can differ depending upon factory settings, approximate heating profiles on a relatively short timescale are needed to capture the behaviour of the unit and the export potential. Possible modelling approaches taking into account these factors are discussed and their application to a case study using generic building types is described

Chapter 7 deals with electricity supply and demand in the context of LZCs. The difficulty of storing electricity and so of matching supply to demand is discussed and how this is important for estimating LZC performance. Although beyond the remit of a ratings system the influence of the type and usage of the electrical appliances on the energy efficiency of a dwelling, it is argued that the reported use of NHER software as an analytical tool is sufficient for them to be considered. Possible methodologies for estimating daily electricity consumption are discussed and variation in the results of each is compared. Finally, a methodology for estimating electricity consumption based on these factors, taking into account the potentially important strategy of export to grid, is proposed for cases where occupant specific input is possible The economic difficulties in net metering are explored, and a model for determining the import/export ratio (and timing) of electricity is proposed.

The simple models used to represent LZCs in this study are still too elaborate for use directly in a HER based on annual energy consumption. Chapter 8 describes the reduction of inputs for each technology to achieve fit-for-purpose representations, taking into account the usefulness to the end user of flexibility in expressing design parameters and the overall effect on the output. Also considered is the case of multiple LZCs installations: to investigate the possibility of diminishing returns in this context, LZCs are modelled in combination to estimate overall export and the carbon displacement potential according to the sizing of each technology.

CHAPTER 2: HOME ENERGY RATINGS AND DOMESTIC ENERGY MODELS: THE BASIS FOR CHANGE

2.1 Introduction

HERs are based on some form of domestic energy model (DEM), which is used to estimate the energy use in a dwelling. Typically, this consists of simple equations that represent energy attributable to space and water heating, lighting and appliance use, and thermal characteristics. The purpose of a HER is not primarily to state the energy consumption predicted by the DEM, but rather to provide a simple measure of energy performance, such as a score on a scale of one to one hundred (e.g. SAP) for comparison.

Proposals for radical changes to HER schemes need to recognise their emphasis. HER schemes may emphasise different aspects of national energy policies and other priorities. For example, existing UK schemes are cost oriented and this may not represent the best platform for integrating LZCs, as required by the EU legislation.

Aside from considerations of how LZC contribution to energy requirement should be represented, there are also the technical issues associated with what level of detail the underlying DEMs can and should support in modelling them. The quantity of input parameters and granularity of results in comparison to the rest of the model should be appropriate. In this chapter the HERs and DEMs in common use in the UK are evaluated for the level of support they offer for modelling of LZCs to justify the selection of the NHER and its underlying DEM as the basis for demonstrating the approach proposed in this thesis. In this, the essential framework of the DEM is left unchanged while some simple additional or improved models of LZCs are incorporated. The approach entails the selection of the most significant inputs for each new submodel and the generation of new reference table data at same level of detail as the existing data. To maintain the level of compatibility with BREDEM-12, an assessment was also made of the existing submodels for estimating energy consumption and climate, to ensure that they had the requisite detail to support the new LZC submodels.

2.2 Emphasis of HER Schemes Worldwide

The variety of circumstances and policy situations in different countries strongly influence the design, emphasis, and use of national HER schemes. Practitioners report the use of such schemes for various purposes, and this can depend upon design features of the rating itself. For example, the USA's foremost rating scheme is used for certification, to ensure that newly built houses are designed to a specific standard and that cheaper mortgages can be made available to the purchasers. Ratings in the UK have been used by local authorities to express improvement in the diverse existing housing stock through a range of energy efficiency measures. The Danish rating certificate has been used more towards informing the homeowner with a list of descriptions of measures that could be applied to the building to make it more energy efficient, and explicitly uses measured data from the occupants' bills. The compulsory rating of a dwelling whenever it is bought or sold has raised the market price of energy efficient dwellings.

HER schemes can be used for different purposes, and flexible design helps to maximise the range of uses to which it can be put. Here the use of HER schemes in the three example countries is shown to demonstrate this range.

2.2.1 The USA's Home Energy Programme

The most widely used domestic building energy efficiency measurement in the United States is the Council of American Building Officials' Model Energy Code

(MEC) introduced in 1993 (International Code Council, 1995). Effectively, this is a checklist of the quality of building construction and heating/cooling systems. Some states and counties within states have amended this code to produce regulations that are more stringent, leading to a variety of HER schemes.

The US Department of Energy supports the ENERGY STAR programme (Environmental Protection Agency, 2006), which uses a DEM to determine whether a dwelling performs better in energy terms than a reference house, built to comply with the MEC. The ENERGY STAR label accredited house must exceed the score awarded to the MEC by approximately 30%, or less in those states that exceed the planning specifications, according to the level of additional requirement. In this sense, the US focuses on certification rather than rating with a comparative score.

The US trend is towards benchmarking a dwelling against a design: verifying that a home reaches a particular standard rather than simply reporting a rating. Reaching this standard with a HER enables the homeowner to obtain a better mortgage, and research suggests that in the US, a better HER will improve the market value of a house (Nevin and Watson, 1998). US HERs apply mainly to new build homes, so there is not such a requirement for varying levels of compliance. HERs and energy labelling are targeted strongly towards homebuilders and purchasers rather than owners.

2.2.2 Denmark's HER Scheme

In Denmark, it has been compulsory to obtain a rating for small buildings (1,500m^2 total floor area or less) whenever they are sold since 1985 (Richalet and Henderson, 1999), (Miguez and Porteiro, 2006). This applies to old buildings as well as new build. One of the stated aims of the programme is to inform the buyer of the energy efficiency of the building, rather than forcing them to meet any particular standard. Only qualified individuals with at least five years experience can give a rating. There is a choice of energy models that can be used in the analysis. The report they produce consists of a rating from A to C with five subdivisions, the energy and water use in the dwelling, and a list of energy efficiency improvements that the owner could make to the building. Both reports consider CO_2 emissions and water consumption. The reports do not separate consideration of the building from that of the occupants but work with measured data about the occupant's water and energy usage habits. The list of improvements constitutes an energy action plan, giving the investment needed, annual savings, and lifetime of the proposal.

Denmark has had a HER scheme in some form since 1981. According to the Danish Energy Agency, in the two years after the latest version of the rating scheme was introduced in 1997, 26% of all homebuyers had made the improvements recommended in the HERs carried out upon sale.

2.2.3 *The UK's HER Scheme*

The British 'Standard Assessment Procedure' (SAP) (BRE, 2001) was introduced in 1995 to offer a generic rating, providing a middle ground between competing commercial HER schemes. The SAP was designed for calculation by hand rather than on a computer, so the DEM is quite straightforward. It has been mandatory for new build houses since 1995, although with no mandatory training for assessors, the quality of the results they obtain is debatable. The UK government's requirement for local authorities to audit their housing stock for energy efficiency has created a strong market for energy rating systems in that area. The National Home Energy Rating (Chapman, 1991) is a popular secondary HER scheme, offering more detailed but broadly compatible analysis for use by planning officers and consultants in gauging improvements to domestic energy efficiency. A key feature of the NHER and SAP is that no predetermined method of compliance is required to obtain a particular rating – the dwelling can be upgraded in a number of ways. This flexibility is a factor in its success.

Newly built homes must be given a SAP rating by law, but the National Home Energy Rating (NHER) allows for manipulation of occupancy assumptions and accounts for electricity use, as well as being compatible with the SAP. In addition, only individuals trained in the use of the software may give a NHER rating. Both the SAP and NHER are based upon variants of the Building Research Establishment's DEM (BREDEM) (BRE, 2001), (Anderson, 2002). BREDEM has been validated against detailed simulation programs and found to perform adequately (Shorrock and Dunster, 1994).

The UK Housing Act of 2004 (HMSO, 2004) requires that an energy audit is performed whenever a dwelling is bought, sold or rented. This has driven the development of a low complexity derivative of BREDEM, the Reduced Data SAP for existing dwellings, which infers details of building form for rapid assessment of local authority building stock. Although this rating is a good marker for general condition of large volumes of dwellings, it is subject to greater errors than more laborious methods. Alongside the addition of this lower complexity variant of the SAP, the revision for 2005 (BRE, 2006) introduces consideration of LZCs on a limited level.

2.3 Adding Elements to a HER Scheme

A major consideration in making additions to a HER scheme is to maintain a consistency in approach. The UK's HERs that are the object of this study are oriented towards flexibility, reflecting an incremental and balanced improvement in the rating as energy efficiency measures are taken on. They are used to demonstrate adherence to building regulations but are also used to suggest additional energy efficiency improvements in the mould of the Danish scheme.

These multiple applications require the foundation of the rating to be rooted in a computational model rather than in the form of a checklist. The energy model on which the addition is to be based must have a sufficient level of data available to feed to the added submodels. Conversely, the submodels should not require an excessive additional level of input data. The level of accuracy in the output from the submodels should be comparable to that of the energy model in the first place.

2.4 Two Candidate Rating Schemes: SAP and NHER

The Building Research Establishment offers three variants of domestic energy models for the UK (Shorrock, 1995). These are BREDEM-8 (Anderson, 1997), BREDEM-9 (BRE, 2006), and BREDEM-12 (Anderson, 2002). BREDEM-9 is the minimal version, which uses a fixed location and does not account for fuel in appliance use, cooking or alternative occupancy patterns. BREDEM-12 additionally accounts for these and incorporates a heating season calculation. BREDEM-8 is a monthly model for specialist applications in passive solar design. The UK's SAP is based upon BREDEM-9, while the NHER is based upon BREDEM-12.

BREDEM-9 takes into account the insulation of the dwelling, efficiency of the heating system, ventilation arrangements, solar gains, and fuel used for space and water heating. However, it does not take into account the building size and type, domestic appliances, heating patterns and variation in external temperatures, or geographical location, using a fixed climate corresponding to the UK mean. BREDEM-9 was implemented by the UK government as a measure of the energy efficiency of the building fabric and heating and hot water system. It does not treat the building services in the level of detail that would allow accurate modelling of the short-timescale contribution of LZCs.

The most recent revision to BREDEM-9 (BRE, 2006) adds consideration of LZCs in the form of solar water heating, photovoltaic cells, micro-combined heat and power, and heat pumps, along with scope for modular additions of future technologies as they become available. These models do not account for variation in the climate through the UK. Exporting technologies are also given a fixed factor for determining export throughout regardless of the sizing of the system relative to the dwelling and the expected electricity load. The new reduced data variant of BREDEM-9 allows for specification of solar water heating and photovoltaic cells but assumes default efficiencies in each case, reducing accuracy further.

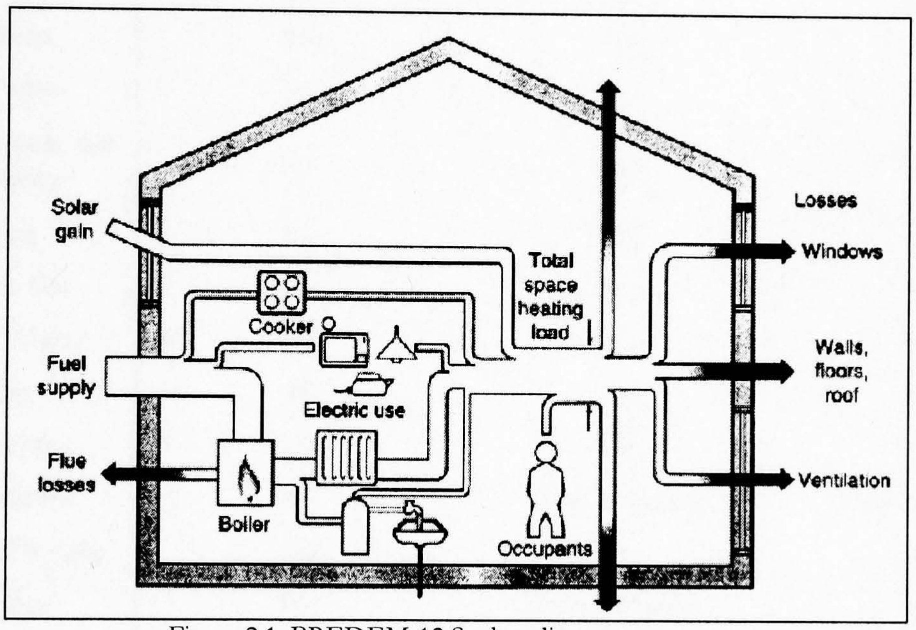


Figure 2.1: BREDEM-12 Sankey diagram
(Anderson, B. R., et al., 2002)

The NHER, provided by National Energy Services (NES), is based on BREDEM-12. As well as the elements covered by BREDEM-9, it includes energy use in space heating, water heating, appliances use, and cooking (Figure 2.1). Heating patterns and the location of the dwelling are also covered. BREDEM-12 uses more of those parameters that have the greatest effect on LZC yield as input, making it more suitable as a basis for modelling them. The output of the BREDEM-12 model, in pounds per annum running costs, is then used in determining the NHER of the dwelling. This figure is corrected for a number of factors: property size and fuel standing charges, fuel types used for heating, and variability in fuel cost over the past decade. BREDEM-12 is compliant with EN 832 (European Committee for Standardisation, 1998), the European standard model for energy performance of buildings. The features of each HER scheme and the DEM behind it are given in Table 2.1.

	BREDEM-9 (SAP)	*BREDEM-12 (NHER)*	*BREDEM-8*
Insulation of Building Fabric	Yes	Yes	Yes
Heating System	Yes	Yes	Yes
Ventilation	Yes	Yes	Yes
Solar Gains	Yes	Yes	Yes
Fuel used in space and water heating	Yes	Yes	Yes
Lighting	Yes	Yes	Yes
Appliance Use	No	Yes	Yes
Appliance Gains	Yes	Yes	Yes
Cooking	No	Yes	Yes
Cooking Gains	Yes	Yes	Yes
Heating Pattern	No	User Definable	User Definable
Location of Dwelling	No	Yes	Yes
Occupancy	No	User Definable	Yes
Fuel Costs	Yes	Undocumented	User Definable
Carbon Emissions	Carbon Emissions Rate	Undocumented	No
Time Step	Yearly	Variable Heating Season	Monthly
Zones	1	2	2

Table 2.1: Comparison of features of BREDEM variants

Although the SAP and NHER ratings comply fully with the BREDEM models, the NHER energy costs calculation allows extended information to be input and taken into account. Input values of fuel costs, occupancy, and appliance use can all be modified by the user. These are to be used at the discretion of the assessor performing the energy evaluation and do not affect the energy ratings directly, but they can be useful to give a better idea of the building's actual running costs. The features outlined above make BREDEM-12 the better option for use as a base for improved representation of LZCs, therefore it was selected for use in this study.

2.5 Selection of LZCs to Represent in BREDEM-12

An objective of this study was to demonstrate how some key LZCs could be represented within BREDEM-12 while considering some characteristics of their seasonal and daily supply profiles. To this end the LZC technologies of solar domestic water heating, photovoltaic cells, and micro-combined heat and power were selected for representation in this study. These were chosen because their generally predictable and profiled patterns of supply of energy could be of use in estimating the importance of timing of supply relative to demand. In addition, those technologies that export electricity could be compared for carbon reducing potential of export. A further selection criterion was that such technologies had the potential to be installed on a large scale in the UK (DTI, 1999).

2.6 Assessing the Suitability of BREDEM-12 for Modelling LZCs

Although the BREDEM models have until now been considered fit for purpose (Shorrock, 1994) they do not contain the necessary detail to model the behaviour of some LZCs, particularly on a seasonal basis. To produce models of the necessary detail and to gain a working understanding of which parameters affect LZC yield, further detail must be drawn from the underlying data. BREDEM-12 simplifies calculations of solar irradiation, hot water load, and electricity load in the dwelling. Profiles for these loads need to be updated to reflect the benefits of LZCs to the dwelling. BREDEM does not cover the export of home-generated electricity, an aspect that is essential in determining the economic viability of some LZCs.

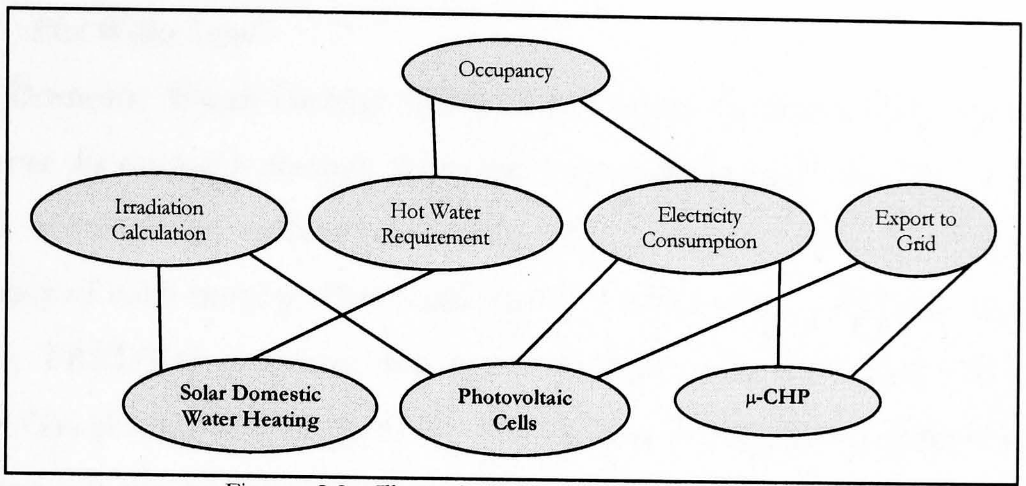


Figure 2.2: Illustration of the factors affecting implementation of some LZCs in BREDEM

Figure 2.2 shows how such calculations affect the final assessment of the benefits gained from some key LZCs. This represents how the estimation of performance of LZCs is affected by the factors, and how some factors affect more than one LZC. This structure will be followed to ensure the foundations upon which LZCs are modelled are adequate for the task.

2.6.1 Irradiation Models

BREDEM-12 calculates irradiance incident upon openings and solar collectors by applying an orientation factor to monthly average irradiation data measured on the horizontal. However, such a method does not give the timing of the irradiation, which is needed to determine whether a solar LZC can deliver energy at the time it is required. The timing of irradiation will also depend upon the atmospheric conditions at the location – with an anisotropic sky the proportion of diffuse irradiation will be greater compared to direct. In this case, the profile of gains will be changed. The orientation of the absorbing surface and its latitude will also affect the timing of received irradiation. It would be difficult to incorporate an iterative calculation for solar irradiation into a DEM, but the approach can be used to research the effect of timing on energy yield.

2.6.2 *Hot Water Load*

Solar Domestic Water Heating (SDWH) is a relatively cheap LZC technology. However, its output is strongly dependent upon the behaviour of the occupants of the building: the volume and timing of demand for hot water affects the efficiency of solar heating. This could also be a factor in the usefulness of μ-CHP output. BREDEM calculates hot water demand from a formula derived by British Gas (Pickup and Miles, 1979). This reflects average daily demand only and does not give the timing of that demand.

It has been found that some households with SDWH systems use significantly less hot water than the British Gas formula predicts (ETSU, 2001). This may be a reflection of hot water demand amongst the public, or it may be that such households are more conscious of water consumption. In each case, there is scope for consideration of water consumption based on the number of water-using appliances and sinks, baths and showers, along with the number of occupants.

2.6.3 *Electrical Load*

BREDEM-12 models electricity demand based solely upon floor area and number of occupants. Like hot water demand, electricity demand is variable between households and is dependant upon occupier habits, but depends additionally upon the appliances owned by the household. The overall demand for electricity and the profile of that demand has a significant effect on the usefulness of energy supplied by PV and μ-CHP. An existing method for modelling lighting and appliance electricity demand based on dwelling, occupants, appliances, date, and time (Stokes, 2004) can be adapted for use in comparing demand with the output of simplified models for PV. The benefit of this model is that calculated variation from the national average demand for occupancy or built forms are optional and can be tailored to suit the level of detail required.

Although the method is suitable for research and validation purposes in this study, it is complex and is not suitable for use with simplified models in practice.

2.6.4 *Export to Grid and Energy Equivalence*

The omission of electricity export effects from BREDEM-12 means that microgeneration LZCs cannot be represented satisfactorily in this sense. PV and μ-CHP technologies both have a dependence upon export prices to help make them economic for the homeowner. Minimum export tariffs are not specified in UK legislation (Elexon, 2004), so the usual tariff for electricity exported to the national grid is around 3p/kWh where the usual tariff for import is 7p/kWh (BRE, 2006) at the time of writing. Variations in renewable electricity supply and demand within the dwelling can change the value of LZC electricity to the homeowner. The coincidence of electricity export and national demand is sometimes quoted as one aspect of μ-CHP that makes it a favourable technology for implementation by electricity distributors (Harrison, 2005).

It is difficult to compare a technology like SDWH with electrically based LZCs. However, it can be considered alongside others in terms of replacement energy avoiding emissions and potential electricity import. The energy from SDWH, PV, and μ-CHP can be compared for timing, magnitude, and general usefulness to the homeowner in terms of import avoided as well as export.

2.7 Fuel-cost versus Carbon Emissions Based Ratings

To date, HERs have been calculated based upon the cost of fuel needed to maintain a dwelling through the year. HERs were introduced in response to the economic pressures of the 1990's, when high fuel costs directed attention to energy efficiency. A high energy rating score meant that a dwelling would cost less to heat, better fulfilling the requirements of the occupants for affordable warmth. However, other concerns are now more prominent in the field of energy efficiency. The demands of the Kyoto agreement and the EU Energy Performance of Buildings Directive are in terms of carbon emissions rather than energy cost. A home that is cheap to run can give rise to more emissions than one with more expensive running costs (Table 2.2).

Although LZCs may save money in the long term, it is difficult to justify their installation cost in financial terms alone. Using fossil fuels remains cheap compared to installing and paying back for a LZC technology, despite the recent upward trend in fuel costs. UK market conditions have reduced electricity price to the minimum necessary cost of production, distribution, and profit margin. The long-term effect on the environment of burning fossil fuels is not covered in this price. A number of alternatives to rating by money cost exist. The energy used could be counted in terms of lifecycle analysis, CO_2 cost per kWh, future market value, avoided emissions, lifecycle emissions, using coal station efficiency and energetic content of source fuel, or the total environmental cost (Coventry, 2003).

SAP 2001	*NHER*	*Costs (NHER 2001)*	*CO_2 tonnes*	*Heating Type*
1	1.5	£1,505	12.1	Direct Acting Electric Boiler (on peak)
36	5	£822	12.2	Manual boiler in Heated Space (Housecoal/pearls)
35	4.5	£769	13.2	Water Storage Heater (off peak)
53	6	£622	7.6	Condensing Boiler 1998 or later

Table 2.2: Comparison of Typical SAP, NHER, Carbon Emissions and Cost, Detached House

The UK's NHER and SAP are based upon annual cost of heating given 20-year average prices, corrected for dwelling size as smaller dwellings are easier to heat than larger ones. The cost of energy used in the dwelling could alternatively be derived using life cycle analysis (LCA) to encompass impacts caused by extracting the fuel, transport, conversion, distribution and use (Proops, J. L. R., et al., 1996). However, LCA methodology is controversial and any result is subject to wide variations in interpretation. While the result would be more complete, it would not give an agreed standard for an energy rating. If LCA were used for analysis of fuel, it would be consistent to use it to rate all the fabrics of the dwelling, complicating the analysis. A full LCA analysis of building fabric would be inappropriate in this context.

2.8 Chapter Summary

Looking at the UK's HERs in an international context demonstrates the approach taken in their formulation compared to that of other countries. The specific requirement for a HER in the UK is for a flexible, straightforward underlying energy model that needs minimal input data. Any additions to this model must have the same form and be consistent with the original.

The BREDEM-9 model as given in the SAP does not capture sufficient detail to model the contribution of LZCs to domestic energy demand accurately. However, BREDEM-12 as embodied in the NHER does include elements such as location and electrical appliance use that make it more suitable for use as a basis for modelling LZCs.

BREDEM-12 does not cover issues of timing of supply and demand, nor does it cover export to grid. Both of these issues are important in gauging the efficiency and the economic viability of LZCs. To get profiled results for output we can use the data given in BREDEM-12 with models for solar irradiation, electrical demand, and air temperature to get a reasonable estimation of the hourly production and export.

In light of the relevant EU and UK legislations' requirement to reduce emissions though microgeneration, it would seem more appropriate to express energy use in terms of CO_2. Calculating emissions in this way would show the effect of energy efficiency measures and LZCs on a home's energy performance more directly. The use of the DEM behind the HER makes it possible to quote a rating based either on adjusted fuel costs or on carbon emissions.

The approach taken in this study is to base the models of LZCs upon the data given in BREDEM-12, extended to provide profiled data so that output patterns could be predicted and compared. This will ensure a consistency between the results of the main energy model and the LZC models implemented alongside it. It will be possible to use model output to provide ratings in terms of monetary cost or carbon emissions, with carbon emissions being the better option for clear representation of LZCs.

CHAPTER 3: ADAPTATION OF CLIMATE MODELS

3.1 Introduction

As the local climate affects some LZC yield directly it is a significant factor in performance estimates. Local conditions can vary considerably in the UK and a particular site may not be equally suitable for all LZC types. The latitude of the location affects irradiation and temperature. The height of the location above sea level, and the proximity of the site to the coast also have an effect. The UK extends geographically from about 50°N to 60°N, and has a cool temperate climate, characterised by changeable weather patterns. The incident irradiation on the horizontal ranges from 884 to 982 kWh/m^2 per annum (CIBSE, 2002).

The hourly distribution of these climatic factors is also affected by location. Day length and therefore the profile of radiation are affected by high latitude, particularly during the winter months (Ronnelid, 2000). This has the potential to affect LZC energy yield profiles and therefore possible exports from microgeneration, on a seasonal and daily basis.

DEMs in the UK typically supply irradiation data in tabular form, using an orientation factor to calculate the effects of tilting the receiving surface. In representing LZCs, there is a requirement for a number of elements of detail in determining irradiation, including intermediate or suboptimal collecting surface orientations, the supply of hourly irradiation profiles, and accounting for seasonal differences in yield. In BREDEM-12, temperature data is given as a monthly average, reflecting the importance of seasonal differences but not permitting the calculation of an hourly profile. More detail is required over the current tables in order to support half hourly models for LZCs; however the detail must be derived from them to keep the results of LZC calculations consistent with those used in thermal calculations for the building. The results of a more detailed methodology can then be reduced to a simplified approach to replace the irradiation data tables. This helps to ensure consistency with the original specifications while presenting regional and system specific variations in data.

3.2 Irradiation models in BREDEM-12 and the SAP

BREDEM-12 supplies a table of mean annual solar irradiation on a south facing 30° inclined plane only, by degree day region (Figure 3.1). It also supplies a table of monthly average daily flux on the horizontal (W/m^2) for calculating solar gains in a dwelling. The latest revision of the SAP supplies a table of annual irradiation under typical collector orientations including tilts from the horizontal and key directions a solar collector might face (BRE, 2006). The tilts covered range to 90° from horizontal and facing due east or west, but the SAP does not give the effects of latitude and regional climatic variation upon the incident irradiation. These two variants of the BREDEM model separately acknowledge the significance of collector orientation and the effect of latitude upon irradiation, but both location and orientation are necessary components in the new irradiation model.

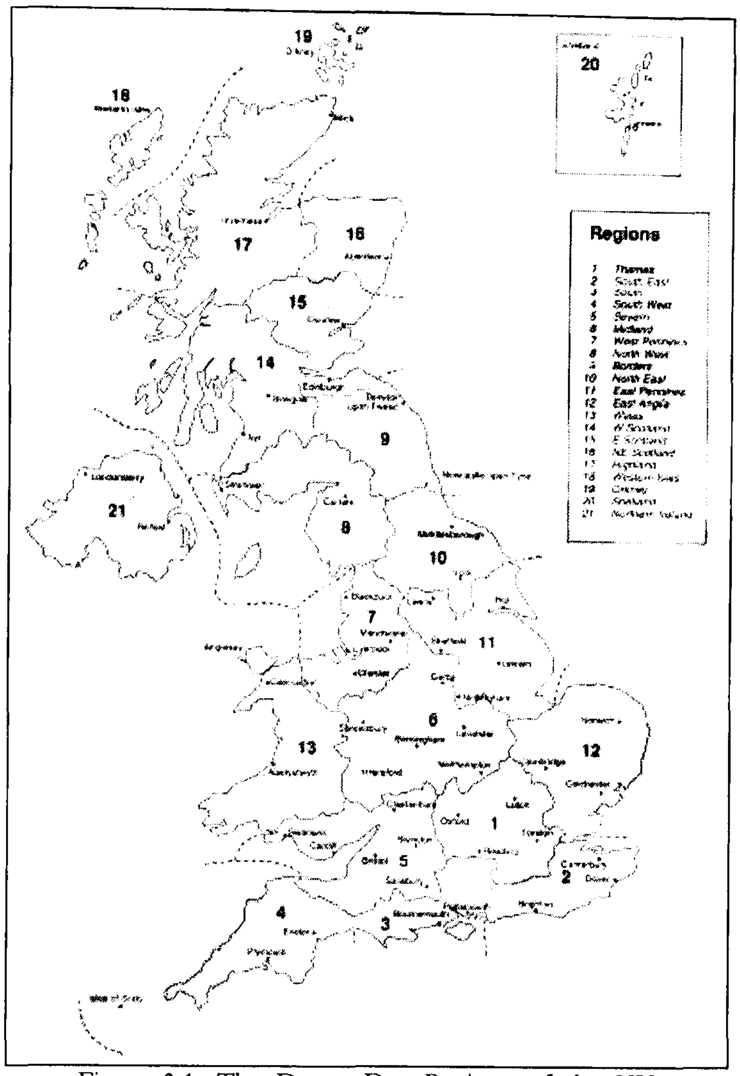


Figure 3.1: The Degree-Day Regions of the UK (Anderson, 2002)

The use of degree day regions in localising the energy rating is one of the strongest arguments for using BREDEM-12 and the NHER software in addition to the SAP, which does not account for location within the UK. This makes NHER software particularly attractive to Local Authorities in the north of the UK where heating requirements are higher than average. An extension of the BREDEM-12 irradiation model to allow for collector orientations must also differentiate between incident irradiation by degree day region.

3.3 Using Climate Datasets

The methodology for deriving climate data for simulation has historically been based on climate datasets gathered from a nearby weather station. There are a number of sources for these records e.g. CIBSE (2002), and Scharmer and Greif (2000). A Test Reference Year (TRY) dataset comprises hourly values describing the typical distribution of temperature, radiation, and wind speed for each month, carefully selected to be representative of the last twenty years. Each month's data may be drawn from a different year, so long as the values for that month are representative of the twenty-year average, to give a year's composite data with all gaps filled by modelling. The specific techniques used are described in (CIBSE, 2002). Each TRY is specific to one location, and gives data typical for a key midmonth day.

Weather monitoring stations recording complete measurements are not numerous or well placed enough to give hourly data for each of the degree day regions in the UK. The 2002 CIBSE guide covers three such locations intended to be representative of the south, centre, and north of the UK respectively. However, the use of 21 degree day regions in BREDEM-12 implies that a more specific measurement of location is needed. To address this issue an approach was used to generate hourly data for each of the degree day regions used in BREDEM-12.

3.4 Description of Irradiation Modelling

The amount of irradiation hitting the collecting surface depends on the solar geometry – the position of the sun with respect to the earth. The latitude of the surface affects the length of the day, the maximum height of the sun in the sky, and the distribution of hourly irradiation, as illustrated in Figure 3.2. A key element in solar geometry is the declination, the angle between the sun and the plane of the equator. In the Northern hemisphere, the declination is highest at the summer solstice and lowest at the winter solstice. From the declination and the latitude, the day length can be found, and the distribution of hourly irradiation through the day can be estimated.

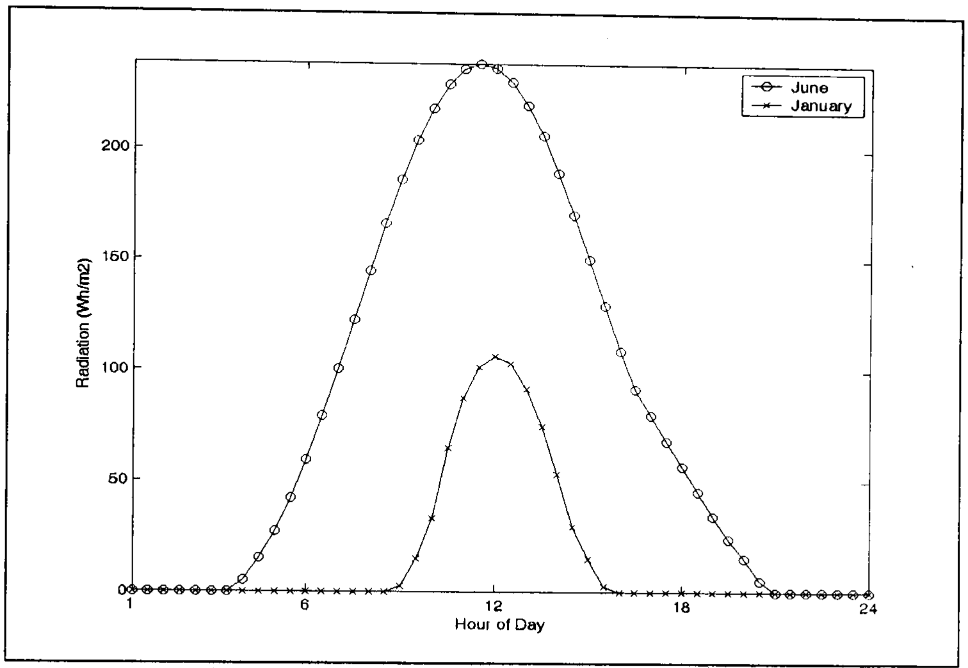


Figure 3.2: Comparison of irradiation profiles of January and June, Thames region.

In an approach adapted from Duffie and Beckman, (1991), several procedures are applied to the raw data measured from the horizontal. The measurements typically consist of the beam irradiation received directly from the sun; and the diffuse irradiation received after scattering by cloud. Some stations record only the total irradiation received, and the proportion of that which is diffuse has to be estimated. For a tilted surface, the composition of the irradiation hitting it is more complex, consisting of beam, diffuse and ground reflected irradiation (Figure 3.3).

An algorithm based on solar geometry is used to separate beam and diffuse irradiation. A dimensionless clearness index is derived to describe the proportion of the irradiation from space (extraterrestrial irradiation) that penetrates the atmosphere and hits the ground. The daily diffuse irradiation is calculated from this along with latitude and regional climate data. Both of these figures are modified for use in calculating the irradiation incident upon a tilted surface. Ground reflected irradiation also becomes relevant in this case. This is normally calculated by a simple geometric method (a generic ground reflectance value is often used). This kind of separated model gives results that approximate the real irradiation hitting a surface. It accounts for the effects of latitude on received irradiance in all its components directly, which is difficult to do by calculating all received irradiation together.

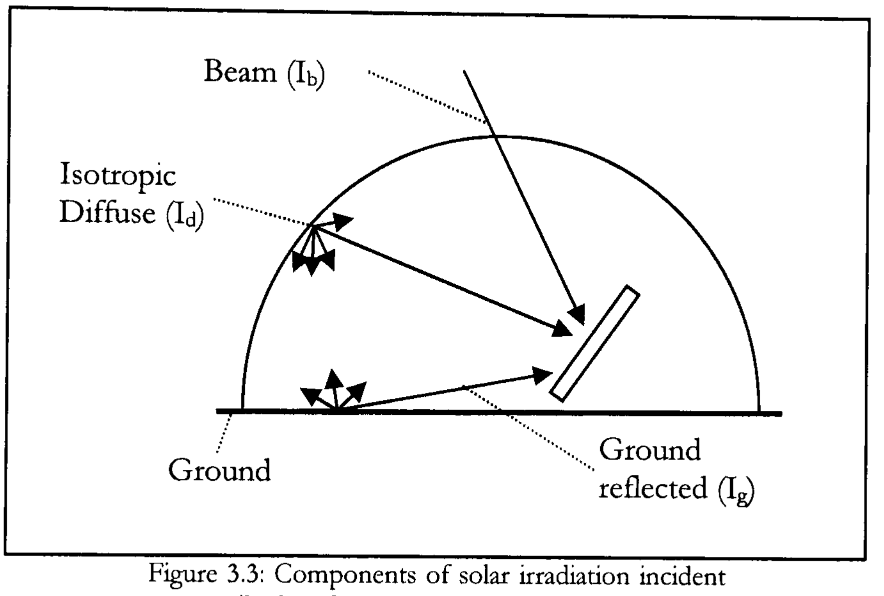


Figure 3.3: Components of solar irradiation incident upon a tilted surface

3.5 Two Candidate Methods

Different models and measured data exist to calculate LZC performance. BREDEM variants have historically used either a simple orientation factor or measured data assuming a particular tilt in the cases where this was needed. Other well validated approaches described in the literature use more detail in their methodology. Two such approaches are the BS5918 method (BSI, 1989), and the Muneer algorithm (Muneer, 1998), which calculates the separate components as described above. Both approaches calculate irradiation according to location and surface orientation, so they are both suitable candidates to use as a base for a modified irradiation model.

3.5.1 BS5918

The BS5918 methodology to calculate an approximation to the irradiation received daily by a solar water heating system, for use in predesign, and is currently the current de facto UK standard in predesign for solar water heating. The orientation factor is based on a visual reckoning against a figure supplied in the document (Figure 3.4). It provides an orientation factor contour diagram that outlines the required factor to be read off from orientation. This allows the proportion of irradiation incident upon a collecting surface to that in the horizontal to be determined. Visual interpolation of tilts and orientations between the marked divisions can be made, allowing greater precision than the BREDEM methodologies.

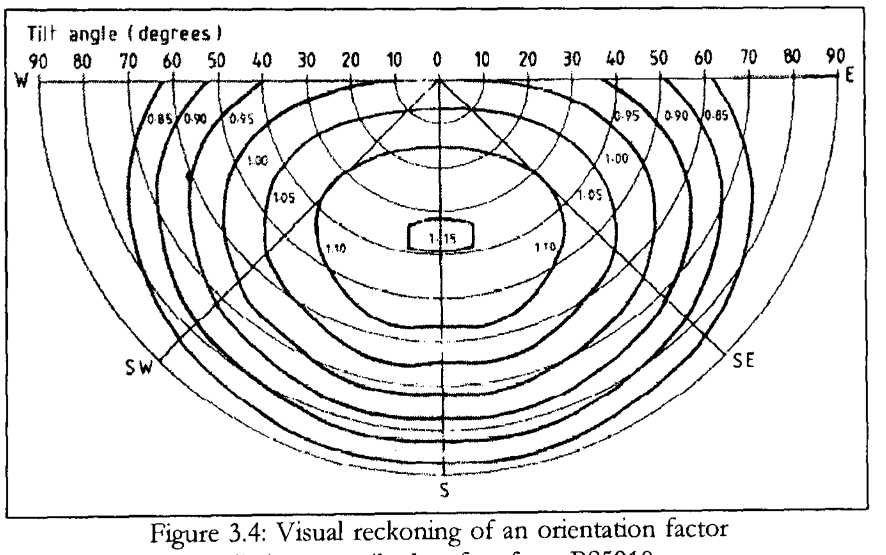


Figure 3.4: Visual reckoning of an orientation factor for irradiation on a tilted surface from BS5918

Notably this method only gives results based on an annual average figure. It cannot account for the strong seasonal variation in incident irradiation. Additionally it is expressed as an orientation factor based upon tilt and azimuth, with no allowance for the effect of latitude.

3.5.2 Muneer Algorithm

The Muneer algorithm comprises the set of calculations as described previously (Section 3.2). The diffuse component of irradiation is calculated using algorithms validated against measured data specific to the UK (Muneer, 1998). To get yearly total irradiation the Muneer method uses midpoint hour and midmonth day. The daily totals are then multiplied with the number of days in each month to get a total in kWh.

This approach covers the effect of latitude on irradiation as well as those of tilt and azimuth, and additionally accounts for solar geometry, providing an hourly profile of irradiation. It was used to fill gaps in the CIBSE TRY irradiation data (CIBSE, 2002), and is used in the European Solar Radiation Atlas software (Scharmer, 2000). The greater detail of the algorithm and acceptance in the field make it the algorithm most appropriate for use in this study, and it has been selected for use in the analysis of the hourly LZC models. However, the algorithm is complex, which is not consistent with the philosophy of simplicity followed in UK DEM specifications. There is a need to choose or adapt a simpler alternative to determine the annual irradiation within the DEM specification. The options are compared in the following section.

3.6 Adapting the Models

The approach taken in adapting the models was to provide an orientation factor according to tilt and azimuth, and multiply with the irradiation on the horizontal provided in the BREDEM-12 tables. The BS5918 orientation factor is intended to be an average for all regions in the UK but does not account for the effects of latitude. Two similar orientation factors were derived based on the CIBSE data and the Muneer results themselves. All three were measured against the results of the Muneer algorithm for overall correlation, to determine which orientation factor method performed best throughout the UK.

3.6.1 BS5918 Orientation Factor

An electronic representation of the BS5918 method was made for this study by digitising the image supplied with the document (Figure 3.5), assigning colours to each region of the image, and using the specified factor corresponding with each colour to find the correct figure. A geometrical algorithm was used to find the point on the image when the orientation and tilt of the surface were entered (Figure 3.6). This permits automated lookup of the data in comparisons of irradiation prediction methods, and demonstrates how it can be used in ratings software. Note that the effects of westerly and easterly tilt were considered to be identical, which is a consistent interpretation of the usual use of the original diagram.

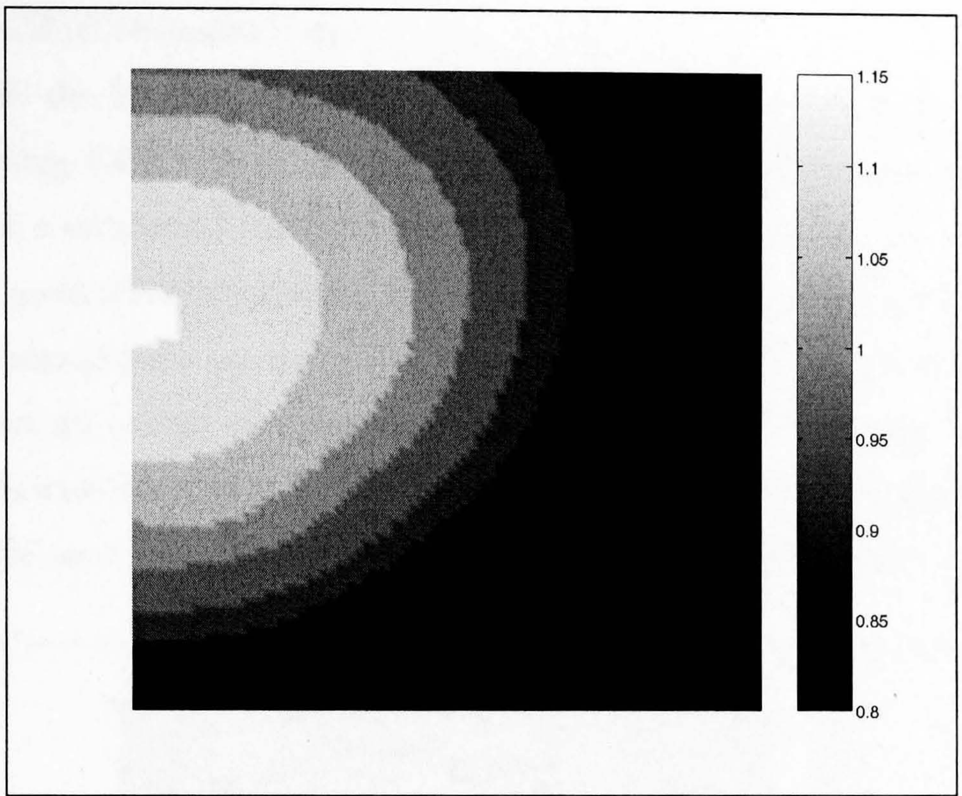


Figure 3.5: Electronic coloured image modified from BS5918

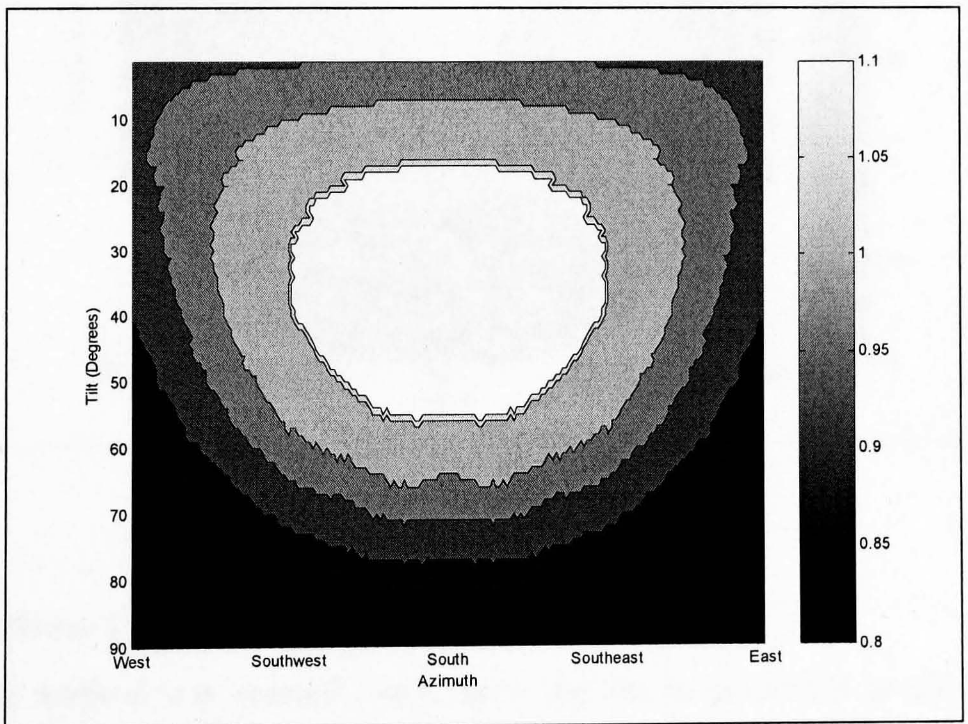


Figure 3.6: Average orientation factors for all sites, modified from original BS5918 figure

3.6.2 CIBSE Orientation Factor

Alongside the BS5918 orientation factor methodology, a method based upon interpolating CIBSE data was considered. The CIBSE data covers three key locations, a number of surface orientations, and gives data by month, so such a method could reflect the additional effects of latitude upon incident irradiation on both an annual and a seasonal basis. In this case an orientation factor was created to express the average irradiation over all three sites, over all months. This was expressed with orientation factors similar to the BS5918 method in Figure 3.7. As the CIBSE sites do not cover all of the UK this could be prone to error.

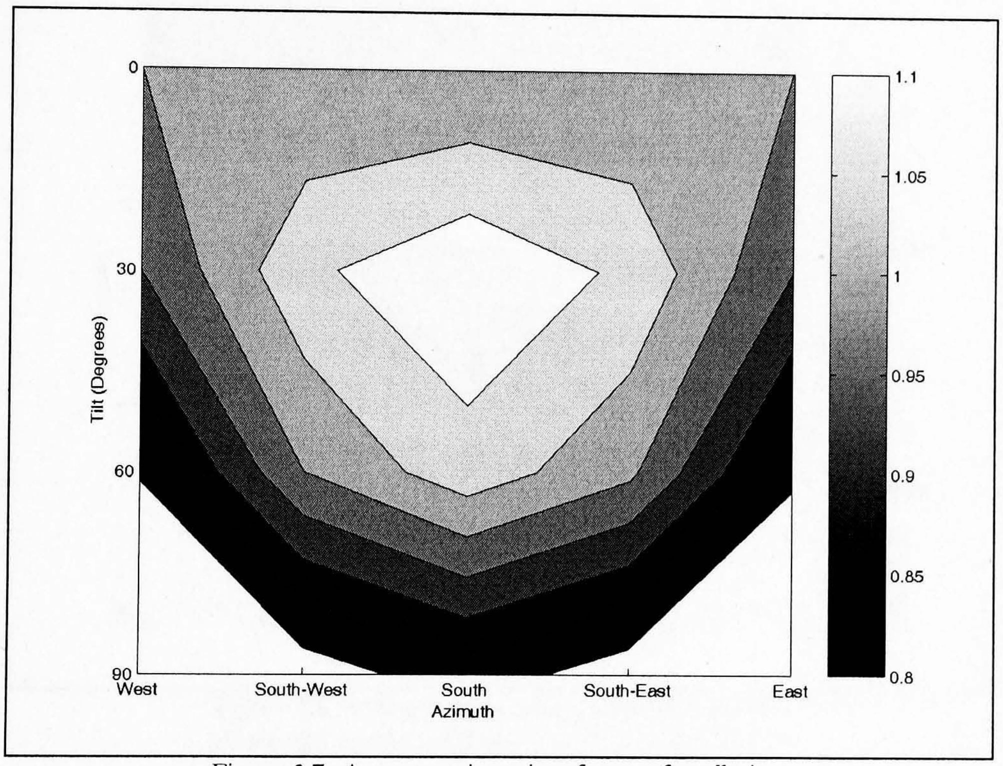


Figure 3.7: Average orientation factors for all sites, all months as calculated from CIBSE data

3.6.3 Muneer Orientation Factor

A similar method was created based upon the results predicted by the Muneer algorithm. To use the Muneer algorithm with the BREDEM-12 data, the figures for flux on horizontal as given in the BREDEM tables were used as the measured data component. This was used with extraterrestrial irradiation to calculate the clearness index, and then separated into beam and diffuse irradiation. As the clearness index is known, the calculation of irradiation on the tilted surface can be made. The average factors of total irradiation on surface inclined and tilted through the probable positions was taken for all the degree day regions of the UK. This was then expressed as a percentage of the irradiation on the horizontal (Figure 3.8). This method uses the output data of the Muneer algorithm and expresses it in a compact and easily useable form. This simplification can lead to drawbacks however, as the effect of latitude on diffuse irradiation is averaged out.

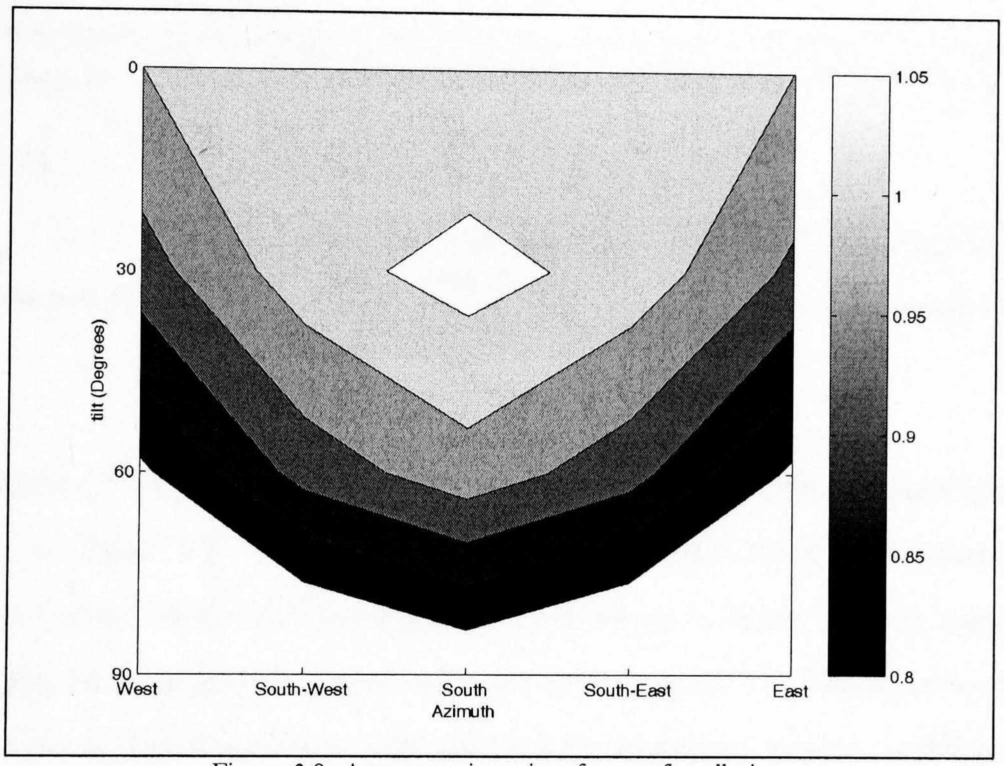


Figure 3.8: Average orientation factors for all sites, all months as calculated from Muneer model data

3.7 Comparison of the Methods

These different approaches can be expected to vary in accuracy. Accuracy in this context is difficult to define because some methods accept more parameters than others do, and it is difficult to identify a reference measured data set. There is also a trade-off of perceived accuracy versus usability. In this study, the Muneer algorithm was taken as the reference case and the methodologies described above were compared against it for how they would predict in a number of situations in the UK. The relative effect of the parameters on the predictions was measured for guidance as to which were the most important to use. For the comparison, implementations of each method were run five hundred times, with the input variables selected at random each time from within the boundaries of the possible values in the UK (Table 3.1). The output given by each methodology could then be compared against the reference case.

Variable	*Description*
Surface Azimuth	This is the direction towards which the surface is tilted. Boundaries are defined as -45° (SW) to 45° (SE).
Surface Tilt	This was taken to vary from zero (horizontal) to 60°.
Latitude	The position north or south of the equator, measured in degrees. This value is between 55° and 62° north in the UK.

Table 3.1: Variables used in irradiation prediction and their boundary values.

The results of the comparison are reported as Pearson correlation coefficient and p-value in Table 3.2. The Pearson correlation coefficient is a measure of the tendency of the results to vary with the explanatory variable. The p-value is the probability of obtaining the same result by chance alone. The table shows that the latitude has a high correlation with the Muneer algorithm results, and this is also reflected in the results of the other methodologies. The azimuth has an optimum figure near zero, and the input parameters vary around this figure. The tilt is also at its optimum in the midrange of the possible input figures. Both of these features would tend to reduce the correlation coefficient with the results. All p-values show that the chance of obtaining the same correlation by chance is less than 5%. The correlation figure of the azimuth is relatively low, implying that the azimuth of the surface has a low correlation with the overall annual received irradiation, given the boundaries of the input variable. Support for this finding can be found in Duffie and Beckman (1995), which offers the rule of thumb that a 10-20° change in azimuth has little effect upon the annual irradiation received.

Variable	*Correlation Coefficient*	*p-value*
Tilt	-0.690	0.000
Azimuth	-0.129	0.004
Latitude	-0.304	0.000

Table 3.2: Comparison of variables versus the results of the Muneer algorithm

The results also depend strongly upon the measured data supplied in the BREDEM tables, as reflected in the high correlation with latitude. The Muneer, CIBSE interpolation, and the BS5918 methodologies were all based on the BREDEM-12 set of fluxes on the horizontal. They therefore give similar results based on degree day regions. The minimum orientation factor specified in the BS5918 method is 0.8 times the irradiation on the horizontal. It is therefore likely to overestimate irradiation in cases where tilt and azimuth are at their extremes.

The results (Table 3.3) show that the Muneer orientation method has a marginally closer correlation with the original Muneer results overall than the results of the BS5918 method do. This is still as low as 0.655 so it is not especially highly correlated. This confirms the suspicion that the effect of latitude and diffuse irradiation on overall yield can be significant, especially in suboptimal orientations. Nonetheless, the majority of installed solar renewable technologies are expected to have near-optimal orientations, where the factor used to modify the irradiation received on the horizontal does not change greatly. For these reasons, and to maintain consistency with the more detailed irradiation model selected for use in these studies, the orientation method derived from the Muneer results was selected as being the best choice for use in a DEM.

Methodology	*Correlation Coefficient*	*p-value*
CIBSE Orientation	0.510	0.000
BS5918 Orientation	0.644	0.000
Muneer Orientation	0.655	0.000

Table 3.3: Comparison of methodology results versus the results of the Muneer algorithm

3.8 Estimating Temperature Profiles

Ambient temperature also has an effect on the performance of LZCs. It is not affected by the tilt of the receiving surface, but it is affected by local conditions. The degree of shading and height of the location above sea level can each have an effect on the average outdoor temperature. However variable temperatures can be in the short term, these variations even out in the long term and generalisations are often made for use in design (CIBSE, 2002). BS5918 gives temperature data in the same way as irradiation: a map of the UK is superimposed with contours giving annual average temperature for particular regions. As this study covers monthly and hourly variations in LZC yield, the level of detail given in the BS5918 methodology is not sufficient.

BREDEM-12 provides average daily temperatures for each month and degree day region. To test the effect of hourly temperature on LZC yield, this data must be obtained or inferred for each degree day region. The CIBSE TRY gives temperature data for the three key UK locations[2], for each month of the year. There is, however, no equivalent to the Muneer algorithm for determining hourly temperature data.

Interpolation was used to give temperatures for degree day regions both between and beyond the bounds of the CIBSE data latitudes. A grid interpolation function

[2] This will be extended to fourteen with the publication of the new 2006 edition of CIBSE Guide J.

in MATLAB software was used to extend the three hourly data sets for each month to each degree day region by latitude.

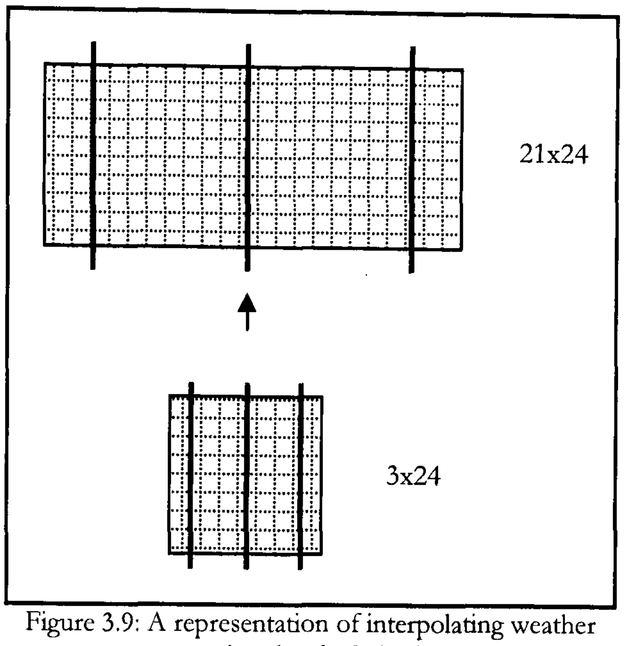


Figure 3.9: A representation of interpolating weather station data by latitude

The three data sets provided in CIBSE guide J are London, Manchester, and Edinburgh. For each month there are 24 hour temperature readings per station, so a 3x24 matrix is made using this. The latitude of each of the three stations is identified, and the 3x24 matrix of temperature values are interpolated into the latitudes of the 21 degree day regions, creating a 21x24 matrix that describes the 24 hour profile for each of the latitudes corresponding to the series of degree day regions (Figure 3.9). To ensure consistency with the BREDEM-12 specification document, the 24 hour temperature profile for each degree day region is adjusted so that the mean is equal to the monthly average as given in BREDEM-12.

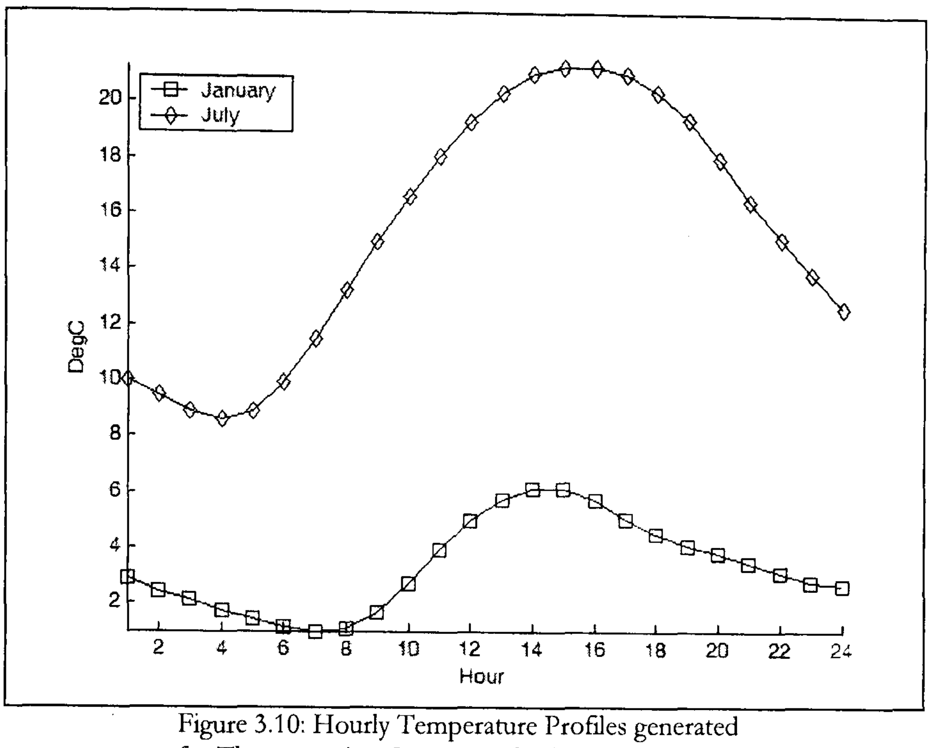


Figure 3.10: Hourly Temperature Profiles generated for Thames region, January and July

Comparison was made at the three key locations between BREDEM-12 data and CIBSE. Notably the CIBSE temperature data is higher overall, with greater extremes in the summer and winter. In this study, the temperature profiles have been distributed in each region so that the average temperature fits with the BREDEM-12 data but the profile of that temperature is consistent with the extrapolation of the CIBSE data. This allows a profiled estimation of temperatures while maintaining consistency with the data provided (Figure 3.10).

3.9 Chapter Summary

The estimation of climate data is significant in the prediction of LZC yields. As the UK climate varies significantly with location this needs to be adequately represented in models for LZCs.

In DEM specifications, the scope for detailed modelling is limited and the data tables supplied in the specification must be consistent with each other. BREDEM-12 calculates climate data by degree day region and any extended methodology must be compatible with this. While detailed climate models were used for the studies on hourly profile of yield, simplified models for irradiation and temperature prediction would be needed for additions to an energy model used in a rating scheme.

A simplified method for predicting irradiation as used in the BS5918 standard document was encoded and compared against similar approaches as derived from measured data for the project. Although it is difficult to give an overall assessment of the accuracy of climate models, candidate models can be assessed based upon their input requirements and general characteristics.

Ambient temperature does not depend upon the orientation of a surface in the way irradiation does, but both are affected by latitude. For use in a home energy rating, the average daily temperatures as expressed in BREDEM-12 are sufficient. For the hourly profiled modelling used in this study, a method based upon extrapolating temperature profiles was developed.

The outcomes of this study were the selection of a particular irradiation methodology for use in determination of LZC yields, and an equivalent simplified methodology for use as an extension to a DEM. These were selected to maintain consistency with each other and with the original specification of the model itself.

CHAPTER 4: SOLAR DOMESTIC WATER HEATING SYSTEMS

4.1 Introduction

Solar Domestic Water Heating (SDWH) has great potential as a relatively low-technology source of renewable energy. Solar water heating systems have been used for over a hundred years, and the technology is well established and understood. It is also suitable for use for water heating in the UK climate conditions. Solar radiation is converted to heat in a collector, through which a working fluid is passed. The heat is typically accumulated in a preheat tank, which then replenishes a storage tank with hot water, removing or minimising the requirement for further heating. Installations in the UK produced about 41 GWh annually in 1997 (DTI, 1999). Because SDWH systems involve thermal processes and are dependant upon the local climate, many variables need to be modelled to get the best level of detail.

Design methods have been developed for use in predesign estimates of how a system would perform (Kenna, 1985), (Duffie and Beckman, 1991). Such methods operate on minimal data input and provide an estimation of annual yield. Design methods are independent of the radiation model used, but are highly dependant upon the output of that model. They are derived from measured data or from simulations.

The daily profile and volume of hot water demand has been found to have a significant effect upon the quantity of useable solar energy yield in some studies (Jordan and Vajen, 2001), (Kenna, 1985). The broad effect of hot water demand profile has been investigated in this study using an hourly model. In this chapter, design methods suitable to represent a SDWH system in a HER scheme are investigated and compared to the results of an hourly model that reflects shorter term hot water demands and solar irradiation profile.

4.2 Solar Domestic Water Heating System Designs

Several variables that affect energy yield are related to the design of the system, for which a number of options are available, specified according to the requirements of the occupants. Part of the process of selecting a model suitable for use in a HER system is to determine which design choices affect the overall useful energy yield the most. The components of a SDWH system and their relative effect on the overall yield are described here in more detail.

A solar thermal system needs, in its simplest terms, a collecting surface to harvest solar energy, and a storage medium in which to place it. The use of other components depends on the design of the system. Systems may be either open or closed loop; they may also be of thermosyphon or of pumped design. An open loop system heats the potable water directly through the collector. A system is closed loop where a working fluid combined with antifreeze is circulated in the collector and heat from this is passed to the preheat tank by a heat exchanger. A thermosyphon system places the preheat storage tank above the collector and allows the warmer fluid to migrate there by convection. A pumped system utilises an electrical pump to circulate the fluid from the tank, through the collector, and back. In the UK, the most common of these combinations is a pumped closed loop system. The climate is cold enough that water in pipes may freeze in winter, and it can be difficult to place a preheat storage tank above the collector in UK homes.

Collector designs fall into two main categories - flat panel and evacuated tube. The flat panel collector, as its name suggests, is a heat-conductive metal plate with tubing attached to it through which the working fluid can move. This is commonly covered with a transparent layer through which irradiation can enter easily, but which restricts heat transfer away from the collector. The evacuated tube design is a glass cylinder holding a vacuum through which internal tubing can carry water. The vacuum is a strong insulator for heat but does allow radiation to pass through. This serves to minimise the heat transfer from the heated water, while maximising solar gains. However, an evacuated tube design is more costly than the simpler flat panel collector.

The typical system arrangement for SDWH in the UK is to have a separate preheat tank and hot water storage tank as in Figure 4.2, but space restrictions in some houses have led to the use of combination tanks, where the water heated by solar thermal is fed directly into the storage tank. Stratification of the warmer and colder water in the tank is encouraged by use of baffles, helping to maintain the efficiency that would be severely reduced by mixing of the layers. A number of other factors can decrease the efficiency of a SDWH system. There are distribution losses in the connecting pipes, 'parasitic' losses from the electricity used for the pump and control system, and the use of a heat exchanger reduces the overall system efficiency. Some modelling approaches consider all of these factors in their estimation of energy yield.

Collector certification information is available though schemes in the USA and the EU: (SRCC, 2006), (Institut für Solartechnik SPF, 2006), see Table 4.1. However, many of the collectors offered in the UK do not have a publicly available certification of their efficiency. The ETSU side by side study (ETSU, 2001a) was commissioned to provide a comparative study of the collectors available in the UK, providing measured data for collector performances under identical conditions. Unfortunately, the results were not expressed in a way equivalent to the more widely recognised system of quoting zero heat loss efficiency and a heat loss coefficient, as commonly used in predesign and modelling methodologies.

	Minimum	*Maximum*	*Average*
Aperture Area (m^2)	0.804	10.656	2.525
Conversion Factor $\eta 0$	0.533	0.937	0.776
Loss Coefficient a1 ($W/(m^2K)$)	1.040	15.650	3.503
Loss Coefficient a2 ($W/(m^2K)$)	0.000	0.051	0.009
Incidence Angle Modifier, Longitudinal (50°)	0.780	0.990	0.924
Incidence Angle Modifier, Transversal (50°)	0.780	1.568	0.957
Annual Domestic Hot Water (kWh/m^2)	N/A	669	503
Annual Water Pre-heating (kWh/m^2)	N/A	893	730
Annual Space Heating (kWh/m^2)	N/A	544	340

Table 4.1: Summary of Collector Specifications as measured by SPF (Institut für Solartechnik SPF, 2006) (168 values)

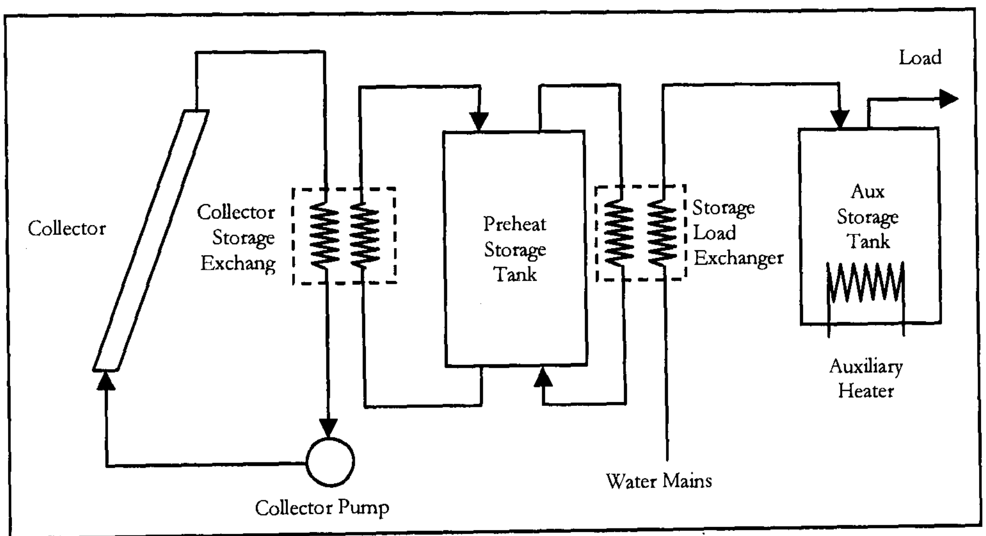


Figure 4.1: SDWH Typical configuration component diagram

4.2.1 *Collector Efficiency Specification*

There is a common standard for measuring the performance of SDWH collectors. A description is given in British Standard 12975-2 (BSI, 2001). A solar collector can be described using a heat balance of irradiation received versus thermal losses, and this is how the performance specifications are expressed. The zero loss collector efficiency η_0 describes the efficiency of the collector assuming there is no heat loss. The heat loss coefficient U_L is then used as a measure of potential heat losses from the collector in $W/m^2/K$.

The Solar Rating and Certification Corporation (SRCC) publish certification data for solar collectors in the US. Although the specifications are the same in principle, they are measured in a different way than the European method. The European method of measuring collector efficiency uses the average of the fluid inlet and outlet temperatures minus the ambient temperature. The US method (ASHRAE, 1977) is to use the difference between the inlet temperature and the air temperature. This disparity in measurement can affect both of the performance specifications. If there is a mismatch, collector performance parameters can be converted from one format to the other, as described in (Duffie and Beckman, 1995: 6.19).

The efficiency of flat plate and evacuated tube collectors is dependant upon the angle at which the radiation hits the surface. To account for this effect an incidence angle modifier is used. Flat plate collectors are optically symmetrical and so require only one angle modifier; evacuated tube collectors require two incidence angle modifiers, one for the transverse and one for the longitudinal plane.

4.3 SDWH Models and Design Methodologies

Given the well established nature of SDWH technology, there are a number of methods for estimating its annual yield. These vary in the number of variables they cover. They range from the simplest methodology, using a few variables in an annual calculation, to the most detailed, using an hourly calculation, incorporating pipe losses and heat exchanger efficiency to calculate the total energy yield. Design methods aim to distil the more effective variables from detailed models into a simplified format. Here the current BREDEM-12 methodology, the British standard for estimating SDWH yield, and a relatively in depth hourly model are shown, to demonstrate the capabilities of the various techniques.

4.3.1 *The Current BREDEM-12 Method*

A formula for calculating SDWH yield is already present in BREDEM-12 (BRE, 2001). The methodology is derived directly from measured data. Some key variables are used to estimate the yield of the collector, given certain assumptions. A utilisation approach is taken: the amount of useful energy that can be collected is calculated from some key system variables.

For 1/LR<0.65:

$$UT = -0.61*\left(\frac{1}{LR}\right)^2 + 0.63*\left(\frac{1}{LR}\right) + 0.35$$

(Equation 4.1)

For 1/LR >=0.65:

$$UT = \frac{0.65}{\left(0.67*\left(\frac{1}{LR}\right)\right)}$$

(Equation 4.2)

$$\frac{1}{LR} = \frac{0.5 f_{sp} S_{30} A_{sp}}{Q_u + Q_t}$$

(Equation 4.3)

Where:

UT is the Useful Total (%)

A_{sp} is the area of the solar panel (m2)

Q_u is the hot water demand (W)

Q_t is the tank loss rate (W)

LR is the load ratio

f_{sp} is collector panel efficiency (%)

S_{30} is radiation falling on a south facing 30° inclined plane for the degree day region (W/m2)

A_{sp} is the area of the solar panel (m^2)

Q_u is the hot water demand (W)

Q_t is the tank loss rate (W)

A variable called the useful total is estimated from the ratio of demand to supply. This is used to modify the total amount of energy yield according to collector area, efficiency, and incident irradiation. The collector is assumed to face due south, with a 30° tilt, as is the standard roof tilt for most UK houses. This methodology was derived from measured data in the UK comprising the two recent ETSU studies (ETSU, 2001a), (ETSU, 2001b). The disadvantage to this method is that it is not based upon recognised measurement of collector and system efficiency. The exact figures required as input are not stated explicitly in the BREDEM-12 document but are intended to be the measure of peak collector efficiency as given in the ETSU document (Henderson, J., personal communication, 2004). However, this measurement has only been taken on eight of the foremost collectors offered in the UK and does not cater for future introductions to the market. To be of use in future situations where the market may change, the BREDEM-12 model has to take SDWH input specifications that conform to British and international standards of testing.

4.3.2 Kenna Method

The Kenna correlation method, as adopted in the British Standards document BS5918, groups the input specifications into three dimensionless parameters *M*, *K*, and *R* (Kenna, 1984). *M* is the ratio of energy available to heat transfer fluid to energy demand, *K* is the ratio of collector loss at demand temperature to peak rate of energy input, and *R* is the number of days of storage available. These parameters are combined to give an annual total energy yield, derived from a correlation between the combination of the parameters and the total yield as calculated using detailed simulation of the equivalent system in TRNSYS (Klein and Beckman, 2000).

$$M = \frac{A'}{L}[H_{tilt} + 0.0432\frac{U}{\eta_0}(T_a - T_c)] \qquad \text{(Equation 4.4)}$$

$$K = \frac{U}{\eta_0} \frac{(T_d - T_c)}{[G_{tilt} + \frac{U}{\eta_0}(T_a - T_c)]}$$ (Equation 4.5)

$$R = \frac{V_s}{V}$$ (Equation 4.6)

$$L = 0.00418V(T_d - T_c)$$ (Equation 4.7)

Where:

H_{tilt} = Annual mean daily irradiation
G_{tilt} = Annual mean daily peak irradiance
T_a = Annual mean daytime air temperature
T_c = Annual mean cold water supply temperature
U = Collector heat loss coefficient
η_0 = Zero temperature loss collector efficiency
A' = Effective aperture area of the collector
V = Daily mean hot water requirement
V_s = Volume of the preheat storage vessel
L = Daily mean load

The three parameters are used to predict the proportion of energy supplied by solar (the solar fraction) in an equation derived by comparison against measured data. Kenna measured the effect of demand profile upon the solar fraction using three examples: a domestic profile, a commercial profile, and a profile peaking at midday. It was found that in cases where the preheat storage held less than the day's demand, the demand profile can have a significant effect on solar fraction, and equivalent equations were given for use in the correlation method. The method has been tested and found to predict within 10% of measured data. This methodology was adopted and used in the Enlightened Planning project (Gadsden, 2001) to predict the potential of solar energy in reducing the local demand for fossil fuels in a study area in Leicester.

4.3.3 Duffie and Beckman System Model

Duffie and Beckman (1991) give detailed integrated system models for SDWH yield, covering many elements of system design and location. A simple combined system model is given in section 10.9 of the book. Most of the models in the book are variations upon this theme, changing in their complexity.

$$\left(mC_p\right)_s \frac{dT_s}{dt} = A_c F_R \left[S - U_L\left(T_s - T_a\right)\right]^+ - \left(UA\right)_s\left(T_s - T_a'\right) - \varepsilon_L\left(\dot{m}C_p\right)_{\min}\left(T_s - T_{Lr}\right) \quad \text{(Equation 4.8)}$$

Where:

m is the average mass of water moved through the collector (kg/second)

C_p is the capacitance rate of water (4180j/kgK)

A_c is the area of the collector

F_R is the collector heat removal factor, allowing for the incidence angle modifier

S is the incident irradiation

U_L is the collector loss coefficient

T_s is the temperature of the store

T_a is the ambient temperature

UA_s is the storage tank loss coefficient area.

T_a' is the ambient temperature in the room in which the storage tank is situated.

ε_L is the heat exchanger effectiveness

T_{LR} is the temperature at which the load is replenished from the mains.

The model has three main components: the representation of the collector, the losses associated with tank storage, and the hot water load. Other descriptive aspects of the system performance are combined into these components, e.g. exchanger efficiency is incorporated into the term accounting for supply to the load.

Euler integration is then used with this equation to get the change in storage tank temperature at each time step, enabling calculation of the useful quantity of solar energy collected, according to the change in ambient conditions. The model is run at a sub-hourly time step to maintain stability but only the data at hourly points are suitable for use in models.

4.4 Hot Water Demand

4.4.1 Calculating Daily Hot Water Demand

Hot water demand is highly variable between households. However, the number of occupants has been found to have some influence over the daily consumption per person. The BREDEM-12 calculation bases demand directly upon the expected occupancy of the dwelling.

BREDEM-12 offers a 20% modification in hot water energy demand for a household that that is deemed by the assessor to have higher or lower consumption than average. This treatment of demand is based directly upon the calculated occupancy of the dwelling, rather than modelling of individual hot water appliances. The BREDEM-12 formula is based upon a British Gas survey of some twenty years ago, agreeing well with a contemporary BRE survey of solar water heaters.

The CIBSE installation guide (CIBSE, 1986) covers eight UK studies into domestic hot water consumption, which give average results between 28 and 69 litres/person day. From this variety of results, they gave a rule of thumb for hot water system design to satisfy the demand of 90% of households.

Recent studies such as (ETSU, 2001b) show a slightly reduced hot water demand compared to the BREDEM-12 figures. Figure 4.2 shows the relative estimates based on CIBSE recommendations, the BREDEM formula, and the most recent BRE field trials at the time of deriving the formula. The ASHRAE handbook recommends allowing for 76 litres of hot water per person per day in design decisions (ASHRAE, 1999).

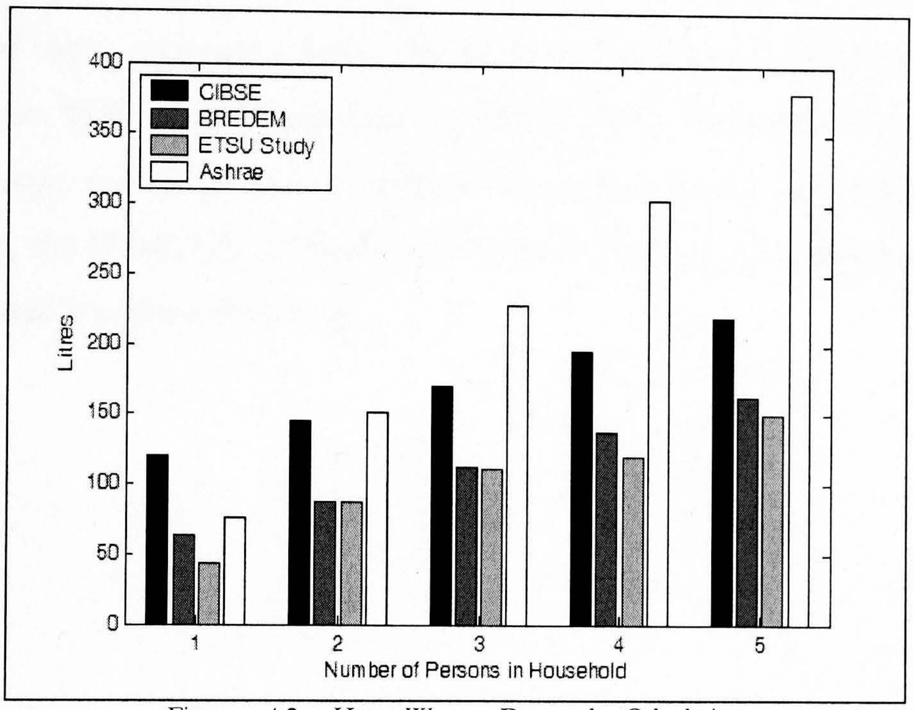


Figure 4.2: Hot Water Demand Calculation Comparison

From inspection of the figure, it can be seen that the ASHRAE recommendation is considerably higher than the others are at higher occupancy. It is designed for the US, and a wider range of climatic conditions than the UK. Like the CIBSE calculation, it is intended to cater for most dwellings in a design capacity and not to reflect the mean of daily demands for all dwellings.

A methodology that sums the hot water draws for each fitting and use was considered for use in giving an estimate of household consumption on a case-by-case basis in this study. Table 4.2 and Table 4.3 give example quantities of hot water associated with specific fittings and uses in the US, according to ASHRAE. The figures are for use as a rule of thumb, and the pattern of usage of such fittings is specific to each set of occupants, so behavioural characteristics dominate. Such a detailed approach would need to account for individual behaviour of each occupant, also making reasonable assumptions for shared usage e.g. occupants sharing laundry loads and food preparation tasks. The frequency of such tasks would need to be defined, with reasonable estimation of number of meals prepared at home per week, and frequency of dishwasher/hand washing use. With a lack of measured profiled data for comparison for the UK, this technique cannot be used confidently to predict overall hot water demand. Therefore, the BREDEM-12 method of estimating daily hot water demand has been selected for use in this study.

Fixture	*Litres/Hour*
Basin	7.6
Bath	76
Dishwasher	57
Kitchen Sink	38
Washing Machine	76
Shower	114

Table 4.2: Hot Water Consumption per Appliance (ASHRAE, 1999).

Use	*Litres/Task*
Food Preparation	19
Hand Dish Washing	15
Automatic Dishwasher	57
Laundry	121
Shower or Bath	76
Face and Hand Washing	15

Table 4.3: Hot Water Consumption per Use (ASHRAE, 1999).

4.4.2 Calculating the Hot Water Load Profile

The timing of demand for hot water can potentially have an effect upon the efficiency of a SDWH system. The use of modified equations accounting for demand profile in the Kenna methodology is a testament to the importance of timing of load to solar fraction. Previous studies have addressed draw off profiles in SDWH by using predefined patterns or by generating stochastic data. An exercise was performed for this study in comparing the calculated SDWH yield when using a daily recurring and a more realistic stochastically generated profile, to determine what effects these might have upon a SDWH model in a HER.

4.4.2.1 Previous Studies

An ETSU study (DTI, 2002b) measured the difference made by changing the demand profile from a single midday draw off to three equally spaced draw offs. It was found that splitting the water demand pattern into separate draw-offs made for a reduced overall yield. The draw off pattern in three sections allowed better utilisation of the solar input during the day, as the tank was kept cooler. However, this pattern also meant that heat was lost from the tank throughout the night. The three draw off profile was assumed to cause more destratification in the tank than the single one, affecting the results for the worse.

Buckles and Klein (1980) compared the performance of generic SDWH systems using a simulation approach, comparing many aspects of the system design for their effect on the solar fraction. The effect of hot water load distribution was investigated by creating a number of standard draw off patterns including one where draw off was non-recurring, one where it was constant, and morning, noon, afternoon, and evening draw off patterns. Each one culminated in the same amount of water drawn daily. Little difference was found between them in the solar fraction. A weekly pattern with substantially different daily demands was created for use with simulations. It was found that the fraction of energy gained from the SDWH system is significantly reduced (up to 10%) with this kind of change in demand pattern, especially where a pattern for daily demand frequently exceeds the storage tank capacity.

Jordan and Vajen, (2000) generated an annual demand pattern on a 1-minute timescale by statistical means. They compiled this by defining four basic load types (short, medium, bath, and shower) and assigning them to probability profiles by season, week, day, and holiday. An example annual profile could then be generated from the components, containing stochastic draw profiles for each size of load according to their probability. They then went on to compare the effect of each load type on the solar fraction. They produced annual profiles removing each distribution profile in turn. This allowed the relative effects of each one to be analysed. They found that removing the probability profile of weekly consumption produced negligible difference in the solar fraction – most likely because this only altered the probability of hot water load due to bathing.

Removing the holiday season had the largest negative effect on the annual solar fraction, followed by the seasonal then the daily profiles. The effect of these variations in demand profile is low when measured below the hourly level. Jordan and Vajen quote the average difference in predicted yield between using an hourly profile and a minute by minute profile as only 3%.

4.4.2.2 Studying the Effect of the Hot Water Demand Profile

For this thesis, a number of experiments in varying the load profile were performed for using a version of Duffie and Beckman's hourly model for SDWH coded in MATLAB (The Mathworks Inc, 2006). A residential hourly hot water use profile was taken from ASHRAE (ASHRAE, 1999), see Figure 4.3, and a sample profile as generated by Jordan and Knudsen's method was taken and they were compared for the useful energy an example SDWH installation could provide annually. This comparison was made in order to determine the effect of load profile upon the solar fraction, to judge whether its effects should be accounted for in a rating scheme.

Some important elements of the Jordan and Knudsen profile make it more realistic than a repeating static daily profile. The profile varies between days so that the effect of storage in the tank can be taken. They provide consumption profiles for a number of average daily demands, so that profiles can be superimposed to arrive at intermediate hot water demands. This superimposition increases the overall demand while keeping individual draw offs at a more realistic smaller size. The load is expressed in litres/hour for all time steps, with the understanding that a profile in larger time steps will have lower average flow rates.

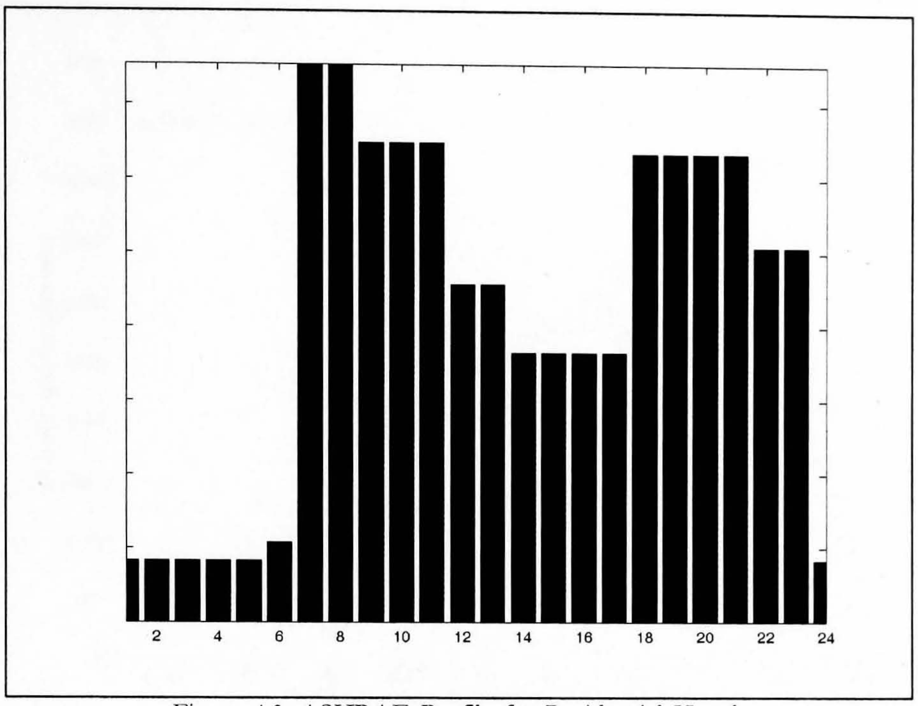


Figure 4.3: ASHRAE Profile for Residential Hourly Hot Water Use (ASHRAE, 1999)

In this study, the profile was interpolated to give intermediate demands between the 100 litre and 200 litre profiles. The models were run 250 times each as a compromise between volume of data and computation time. Both were given the same set of input variables for each run, with each of the variables selected at random between the sensible maximum and minimum. The annual solar fraction for each model for each run was taken. The difference between the set daily profile from ASHRAE and the minute by minute profile from Jordan and Knudsen was measured for comparison. Figure 4.4 shows the results of the comparison.

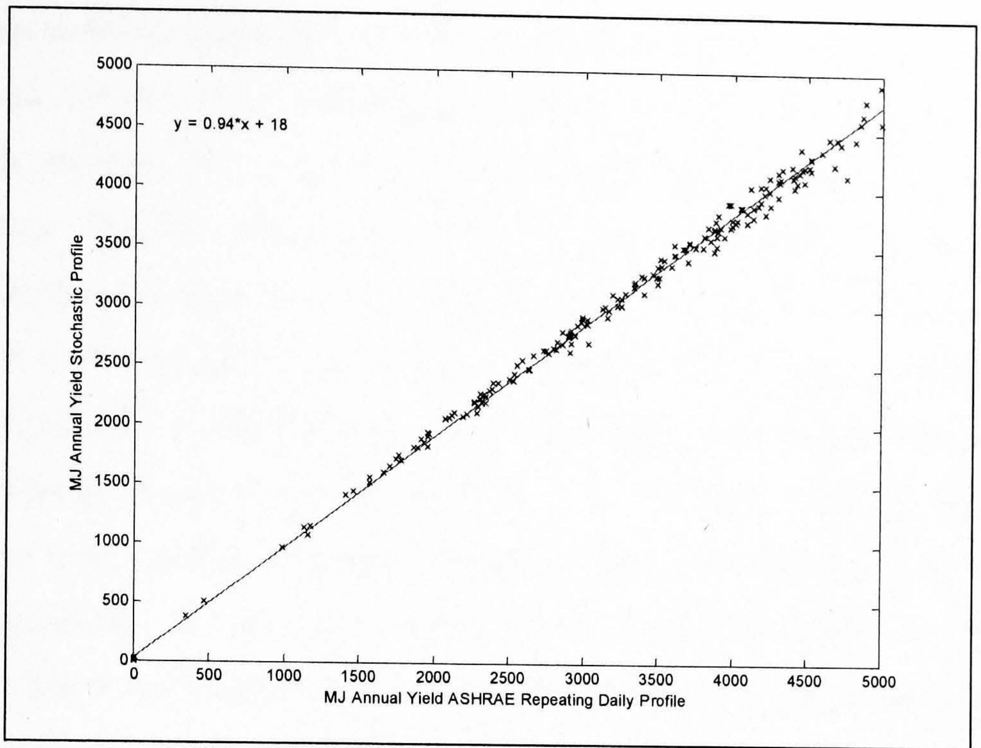


Figure 4.4: Comparison SDWH yield ASHRAE Profile Versus Stochastic Profile, 250 Runs

As shown in the figure there is some 6% reduction in yield predicted on average with a stochastic non repeating pattern of demand. This agrees with the ETSU study that found that most systems tested showed a slight reduction in efficiency under a (regular) split draw-off.

4.5 Chapter Summary

SDWH has great potential for use as a relatively simple and low cost renewable energy technology. It has the largest installed base of all the domestic renewable energy system types in the UK. Many different system designs are in use, but their yield tends be similar on an annual basis and design method techniques can model this from a reduced set of variables. The variables of most importance in system design are related to the collector performance. These can readily be sourced from manufacturer data.

There are different approaches to design methods: correlation methods whereby groups of dimensionless variables are correlated with measured data, utilisation methods whereby the useful monthly total yield is calculated, and short cut simulations whereby single days of the month are simulated and assumed representative. Examples of all three approaches have been studied. Design methods work with implicit simplifying assumptions about the specification and components of a SDWH system. The compatibility of a model with the data available as input was an issue in this work; as models had to perform adequately given the data available. However, system specifications derived from tests are more applicable to simulation. The effect of the differences in occupant behaviour between installations needed to be accounted for in this study, and this incorporates the effect of profiled hot water demand. A compromise solution between detailed simulation and the simpler design methods was sought as the best way to proceed. An hourly short cut model suitable for approximate estimation of yields was selected for use in this study.

The quantity and profile of water demand is one occupancy-related factor that has the potential to affect the overall efficiency of a SDWH installation. However, the effect of demand profiles combined with storage and collector size is not straightforward, especially combined with the effects of location. With an hourly model, using a stochastically generated demand profile means some 6% reduction in performance on average compared to using the less realistic repeating daily profile. The hourly yield can be used for further research in the timing of energy flows, and is the basis for the derivation of simplified models more fitting to the constraints of an energy rating.

CHAPTER 5: PHOTOVOLTAIC SYSTEMS

5.1 Introduction

Solar cells are one of the most high profile of LZC types but have a high installation cost and consequently a long payback time. While they may repay the embodied energy used in their manufacture within as little as two years, the economic payback time may run to twenty years and more (Wilson and Young, 1996). An approximation of photovoltaic module performance can be arrived at from measured irradiation data but variations in cell specification, balance of system performance, and shading or soiling of the cells can affect their performance substantially in practice. It was estimated that there was just under 10.9MW of photovoltaic capacity in the UK in 2005 (DTI, 2005b). Given the typical high installation cost of photovoltaic systems, the value of the electricity used in the dwelling or exported can be an important issue in payback time for domestic grid connected systems.

Sizing and design methods for photovoltaic systems are available in the literature (Duffie and Beckman, 1991), (CANMET, 2002), and (SANDIA, 2006). However, measured data relevant to UK installations has only become available relatively recently and field trials are ongoing (BRE, 2005). A challenge specific to this study is in selecting a model that will give results to the level of detail required. The effects of daily profile of generation are a consideration, but over specification of the level of detail of the model could lead to delays in computation time and the exposure of the limitations of the input data. The technology data selected for input must be readily available from the product specifications. The availability of such data for use as input variables is also an issue in this study.

Design methodologies have been reviewed here to determine which variables are both of significance in use in a simplified method, and can be easily collected in an energy assessment scenario. The determination of default component specifications is also of key importance in the proposal of a new model. Balance of system components can have a major effect upon the calculated energy yield but their efficiency in operation is not addressed in much detail within such hourly modelling design methodologies. An alternative is to select reasonable default performance figures for components, appropriate to the UK market and climate as can best be taken from measured data.

5.2 Technology Description

A typical UK photovoltaic system consists of cells arranged in modules forming an array, with balance of system components of load control, an inverter for export to grid (Figure 5.1), or a battery in the case of autonomous operation (Figure 5.2). The efficiency of each component has an effect on the overall efficiency of the system and on the instantaneous yield.

The basic unit of power conversion in a photovoltaic system is the solar cell. A solar cell can be made of e.g. silicon, alloyed with impurities ('doped') to produce a semiconductor. The semiconductor can be doped either to create extra electrons in the valence band ('n-type'), or to create an electron deficiency ('p-type). The doping changes the silicon from being an insulator to being a conductor. A *p-n junction* can be formed by interfacing n-type and p-type semiconductors. Photons from incident irradiation can be absorbed by the semiconductor, and produce an extra electron in the valence band. This creates electron hole pairs, which migrate to the junction and diffuse, creating an electric current. Excess energy is lost as heat, reducing the electrical efficiency of the cell. Electron hole pairs are also subject to recombination, whereby they fall back into the valance band and recombine with the holes. This is caused by impurities in the cell material, and higher grade materials in cell construction can mitigate this effect.

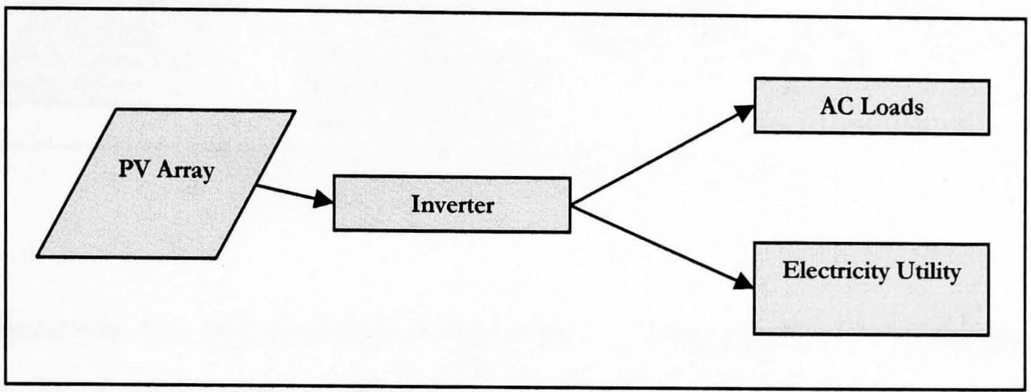


Figure 5.1: Diagram of grid connected PV system

There are various methods used to manufacture the semiconductor that forms the cell. The choice of method and material affects the cost and also the efficiency of the cell (Table 5.1).

Technology	*Amorphous Silicon*	*Polycrystalline Silicon*	*Monocrystalline Silicon*
Typical Efficiency	3-6%	10-13%	12-15%

Table 5.1: Typical Efficiencies of Solar Cell Technologies (CANMET Energy Technology Center, 2002)

The output of the solar array depends on the incident irradiation and the temperature of the cells. The voltage supplied by the cell decreases with increasing temperature, and maximum power point tracking (MPPT) may be used in the balance of system hardware to keep the balance between voltage and current within the maximum power range.

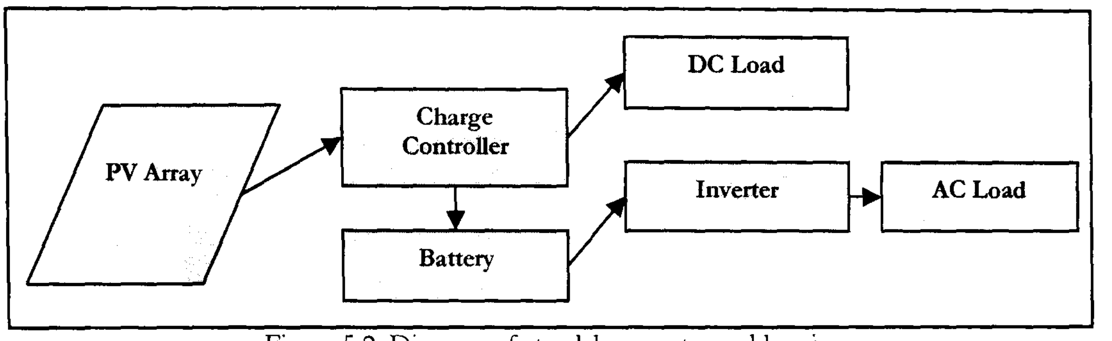


Figure 5.2: Diagram of standalone system addressing AC and DC loads.

Specifications for the common components of photovoltaic installations can usually be found in the manufacturer's literature. Databases and test result documents are also readily available for some cases. The database maintained at SANDIA laboratories is a record of some solar cells on sale in the USA, with details of their measured performance under reference conditions (SANDIA National Laboratories, 2006). Autonomous photovoltaic systems require battery storage to prevent loss of load. The battery is subject to storage losses and inefficiency in energy conversion. Load control mechanisms are typically put in place to conserve battery life, but may affect the efficiency of the system as a whole.

5.2.1 *Solar Cell Specifications*

Common measurements used in the specification of solar cells can be used to obtain an efficiency dependant upon temperature and radiation. They are commonly expressed as a figure for maximum power point efficiency at reference temperature modified by the maximum power point efficiency temperature coefficient, as with Duffie and Beckman. The calculation can be done cell by cell, multiplying up the effects to the level of the array (Markvart, 2000). Care must be taken not to mix the variables from these alternative methods of specifying cell efficiency, as they are not compatible with each other. SANDIA laboratories provide a database of cell specifications, a summary of which is shown in Table 5.2:

Duffie and Beckman give a procedure to calculate the two key variables from manufacturer specifications. They give the maximum power point efficiency as:

$$\eta_{mp,ref} = \frac{I_{mp} V_{mp}}{A_{module} G_T} \qquad \text{(Equation 5.1)}$$

The maximum power point efficiency temperature coefficient is given as:

$$\mu_{P,mp} = \eta_{mp,ref} \frac{\mu_{VOC}}{V_{mp}} \qquad \text{(Equation 5.2)}$$

Where:

$\eta_{mp,\,ref}$ is the maximum power point efficiency at reference temperature

I_{mp} is the current at the maximum power point

A_{module} is the area of the module

G_T is the reference irradiation

$\mu_{P,\,mp}$ is the maximum power point efficiency temperature coefficient

V_{mp} is voltage at the maximum power point

μ_{VOC} is the temperature coefficient of the open circuit voltage

	Minimum	*Maximum*	*Average*
Area (m^2)	0.058	10.78	0.96
Short-circuit current (A)	0.37	34.72	5.07
Open-circuit voltage (V)	10.7	101	29.62
Current at the maximum-power point (A)	0.32	30.86	4.59
Voltage at maximum-power point (V)	8.25	73.5	23.09
Temperature coefficient for module Voc (V/°C)	-0.492	-0.0425	-0.11
Maximum power point efficiency at reference temperature (%)	4.9	15.3	10.3
Maximum power point efficiency temperature coefficient (W/°C)	-0.0007	-0.0002	-0.0005

Table 5.2: Summary of Cell Specifications as measured by (SANDIA National Laboratories, 2006) (127 entries)

Manufacturer specifications do not always give the maximum power point cell efficiency and temperature coefficient in which case the Duffie and Beckman equations must be used to obtain the figures needed in design methods,

5.2.2 Load Control

MPPT maintains the operating voltage of the array at a value that maximises array output, by changing the impedance of the circuit of the cells. This power tracking has losses of up to 10% associated with it. The voltage of MPPT can be assumed as being independent of irradiance, and can be estimated at 80% of open circuit voltage under standard irradiance conditions. The literature suggests that MPPT is used in most modern PV systems, and this use is assumed in the design methods presented here. The MPPT is covered with a factor for power conditioning equipment in design methods.

5.2.3 Inverter Efficiency

The Inverter is used to convert the DC electricity generated by the photovoltaic array into AC electricity suitable for use in a normal circuit in the home or for export to the electricity grid. Typically 5% or more of this electricity is lost as heat in the conversion process. The inverter efficiency depends upon the open circuit current being a maximum at nominal input power. The efficiency is expressed as the ratio of AC power to DC power. The efficiency of the inverter is usually around 95% but can fall to 75-80% if it continuously runs under part load. Conversely, an inverter sized too small may be subject to saturation at times of high incident irradiation, cutting out when yield would be highest. Although design methods allow for inverter efficiency, they assume correct sizing and do not consider possible saturation effects explicitly.

5.2.4 Batteries and Charge Regulator

In cases where the photovoltaic system is not connected to the grid, battery storage may be used. The pattern of use of batteries can affect their lifespan. If a state of deep discharge is reached often, it can reduce the useful life of the batteries. Therefore, battery storage systems are sized to avoid deep discharge, maintain a low capital cost, and provide sufficient storage to maintain supply, while accounting for daily and seasonal effects.

Lead acid batteries are vulnerable to cycling effects in their discharge cycle. Cycling issues affect the life and maintenance of the batteries. The charge regulator component prevents excessive discharge by disconnecting from the load if the voltage supplied by the battery falls below a particular value. The load will not be reconnected until the battery voltage returns to a state higher than this value. While the battery is supplied by the photovoltaic array the function of the charge regulator is to limit the maximum battery voltage to prevent overcharging. Batteries also suffer a penalty in storage efficiency because the voltage is higher during charging than at discharge. Storage efficiencies for lead-acid batteries are in the region of 85-90%.

Design methods tend to calculate the useful contribution of battery storage on a monthly basis. This is derived from example measured data from standalone systems.

5.3 Simulation, Sizing and Design Methods

The calculated performance of a photovoltaic system is affected by some key elements in its specification. The size of the array and the grade of silicon used in its manufacture are instrumental to the power output. The location and orientation of the array, the size of the inverter used, and the amount of battery storage also affect the useful total yield.

Design methods all use similar principles to calculate the yield of a photovoltaic system but differ subtly in their implementation. In methods other than detailed simulation, factors are used to represent the effect of balance of system components and the emphasis of the modelling work is on the efficiency of the solar array and the effect of temperature and irradiation upon it. There is therefore an onus upon the modeller to select appropriate efficiency values for balance of system components and potential inhibitors to array performance.

Most design methods cover both those systems with battery storage and those that are connected to the grid directly. An additional calculation is performed to determine the performance of the battery system. Sizing the system is also a concern and utilisation methods are used to calculate how much storage is required or how much solar generated electricity can be used within the dwelling on average. Although utilisation methods are useful for estimating the performance in the case of a battery storage system, the estimation of export in a grid connected system requires a comparison with daily demand. In this study, sample daily electrical demand profiles are available for comparison; therefore the hourly calculation is used independently of utilisation methods to obtain an hourly average yield for the typical day of each month.

Doubt has been cast upon the veracity of hourly modelling techniques given shorter term fluctuations in irradiation (Ransome and Funtan, 2005). This can lead to conditions where the array is subjected to low irradiation for much greater proportions of the hour than an hourly calculation might suggest, and to short periods of high irradiation without the associated build up of heat in the cells. It is also claimed that the effect of soiling of cells, shading, cell degradation, and inverter clipping are not covered sufficiently well in models, even in detailed simulation programs. To reconcile the hourly nature of the design method models with the shorter term effects that may give rise to error, a validation and recalibration exercise is performed here using measured data on the performance of some PV systems in the UK.

Design methods for calculation of hourly yields can be quite similar in the way they are constructed: an hourly efficiency is calculated for the solar array and factors are used to represent the efficiency of balance of system components. Because of the lack of variation amongst design method models for PV, the leading half-hourly methodology was deemed suitable without a comparison study of other models in this case. It is suitable for use with manufacturer's specifications and local climate data. The model comes from Duffie and Beckman and is described below.

5.3.1 The Duffie and Beckman Hourly Model

Duffie and Beckman give an hourly model for photovoltaic system electricity yields (Duffie and Beckman, 1995). This is based upon the efficiency and the temperature coefficient, remembering that MPPT is assumed throughout.

$$\eta_i = \eta_{mp,ref}\eta_e$$

$$\left[1+\frac{\mu_{mp}}{\eta_{mp,ref}}\left(T_{a,i}-T_{ref}\right)+\frac{\mu_{mp}I_t}{\eta_{mp,ref}}\frac{1\times10^6}{3600}\frac{\tau\alpha}{U_L}\left(1-\eta_{mp,ref}\right)Z_i\right]$$

(Equation 5.3)

$$E_i = \left(\eta_i A_{Array} I_t\right)\times\frac{1\times10^6}{3600}$$ (Equation 5.4)

Where:

η_i is the average efficiency for time step i

$\eta_{mp,ref}$ is the reference maximum power point efficiency

η_e is the efficiency of power conditioning equipment

μ_{mp} is the maximum power point temperature coefficient

$T_{a,i}$ is the ambient temperature for the time span i

T_{ref} is the reference temperature for the cell specification

I_t is the incident irradiation upon the surface

$\tau\alpha$ is the transmittance absorptance product of the cells

U_L is the loss coefficient of the cells

Z_i is the correction factor for irradiation angle

A_{Array} is the area of the array

E_i is the monthly average array electricity output for time span i

The correction factor Z_i is an empirical fit to the degradation of performance due to the angle of sunlight to the cells for that time step. It is approximated from the solar geometry and clearness index.

$$Z_i = \left(\frac{I_o}{I_T}\right)^2 (a_1 b_1 + a_2 b_2 + a_3 b_3) \quad \text{(Equation 5.5)}$$

$$a_1 = R_b^2 + \rho(1-\cos\beta)R_b + \frac{\rho^2(1-\cos\beta)^2}{4} \quad \text{(Equation 5.6)}$$

$$a_2 = R_b(1+\cos\beta - 2R_b) + \frac{\rho(1+\cos\beta - 2R_b)(1-\cos\beta)}{2} \quad \text{(Equation 5.7)}$$

$$a_3 = \left(\frac{1-\cos\beta}{2} - R_b\right)^2 \quad \text{(Equation 5.8)}$$

$$b_1 = -0.1551 + 0.9226k_T \quad \text{(Equation 5.9)}$$

$$b_2 = 0.1456 + 0.0544\ln k_T \quad \text{(Equation 5.10)}$$

$$b_3 = k_T(0.2769 - 0.3184k_T) \quad \text{(Equation 5.11)}$$

Where:

I_o is the monthly average extraterrestrial irradiation

I_T is the incident irradiation on the tilted surface

R_b is the ratio of beam irradiation on the array to the horizontal

β is the tilt angle

ρ is the ground reflectivity

k_T is the clearness index

The methodology goes on to use utilisation methods to calculate the useful average hourly output, accounting for variations in supply on a sub-hourly level. The critical radiation level that exceeds the monthly average load for the hour (Φ) is used to determine the proportion of generation that exceeds the load and the proportion that goes towards meeting it. The averages of these terms are found by summing over the hours of the day.

$$\Phi = \exp\left\{\left[a + b\frac{R_n}{R}\right]\left[X_c + cX_c^2\right]\right\} \qquad \text{(Equation 5.12)}$$

$$X_c = \frac{L_i}{A_{Array}\eta_i I_T} \qquad \text{(Equation 5.13)}$$

$$a = 2.934 - 9.271K_T + 4.031K_T^2 \qquad \text{(Equation 5.14)}$$

$$b = -4.345 + 8.853K_T - 3.602K_T^2 \qquad \text{(Equation 5.15)}$$

$$c = -0.170 - 0.306K_T + 2.936K_T^2 \qquad \text{(Equation 5.16)}$$

Where:

X_c is the critical radiation level for the hour
L_i is the average load for the hour

Once the critical radiation level and the total generation are found for each hour, the split between the electricity supplied to the load and electricity exported or stored can be determined for that day.

If the system has battery storage, the battery efficiency and utility are calculated by an empirically derived formula. The total 'dumped energy without storage' is the battery storage efficiency multiplied by the ratio of excess energy to load. Two figures are important in the estimation of battery performance. These are the remainder of the supply after direct consumption, and the ratio of battery capacity to load. The upper limit on energy supplied to load is the lesser of these. These two figures are used in an empirically derived equation to predict battery performance.

5.4 Comparison and Refinement against Measured Data

Hourly measured data for domestic PV installations is difficult to obtain in the UK. However, data is available on typical annual yield for a number of systems, and for daily yield from some (ETSU, 2003). A year's worth of hourly measured data for a typical system in the Nottingham area was also obtained for validation of the output of the hourly model (Firth, S., personal communication, 2005). Photovoltaic yield and import from the grid were measured and export was derived from this.

The array consists of 18 BP585 panels, giving 1.53 kWp. A SMA 'Sunny Boy' 1100 inverter rated at 1.1kW is used. The occupancy profile is 'elderly retired', implying that the occupants stay within the house during the day. The specifications of the components as described by the manufacturers are given in Table 5.3 and Table 5.4.

	BP 585
Maximum power (Pmax)	85W
Voltage at Pmax (Vmp)	18.0V
Current at Pmax (Imp)	4.72A
Warranted minimum Pmax	80.8W
Short-circuit current (Isc)	5.0A
Open-circuit voltage (Voc)	22.1V
Temperature coefficient of Isc	(0.065±0.015)%/°C
Temperature coefficient of voltage	-(80±10)mV/°C
Temperature coefficient of power	-(0.5±0.05)%/°C
NOCT	47±2°C
Maximum system voltage	600V
Maximum series fuse rating	20A

Table 5.3: Specification of the BP 585 photovoltaic module (BP Solar, 2003)

	Sunny Boy 2500
Recommended peak power of the PV-panels PPV	1500WP
Input voltage range	139…400 V DC
Maximum input current IPV, max	10 A
Nominal output power PAC, nom	1000W
Peak Power	1100W
Total Harmonic Distortion of output current (with KU AC < 2 %,PAC > 0.5 PAC, nom)	THD < 4 %
Maximum efficiency	93.5%
Internal consumption in operation	≤4W
Internal consumption in stand by	0.1W
Size (w x h x d)	322 x 320 x 180 mm
Weight (approx.)	21 kg

Table 5.4: Specification of the Sunny Boy 1100 inverter (SMA, 2001)

This measured data was taken for comparison with the output of Duffie and Beckman's hourly model as implemented in MATLAB (The Mathworks Inc., 2006). The input variables are shown in Table 5.5. The correction factors used in this model, although complex, apply directly to the module that is receiving irradiation rather than to storage. This means that the annual yield of a grid-connected photovoltaic system can be largely dependant upon the received irradiation. The measured yield for the Nottingham system is shown as a half-hourly average Wh in Figure 5.3. The yield calculated by the Duffie and Beckman hourly model using the component specifications and location variables is given in Figure 5.4. A factor to describe inverter efficiency was introduced so as to compare the calculated output with the measured data. Inverter efficiency has been treated in this way in the well-validated RETScreen software (CANMET Energy Technology Center, 2002). The calculated version is an idealised representation of the energy yield that does not reflect the variations in the measured data. An overestimation of yield at lower light levels and an underestimation of the peaks in irradiation can be seen clearly on the calculated figure, compared to the figure showing measured data.

Variable	*Value*
Area	11.32
Array Losses	0.05
Module Efficiency	0.135
NOCT	47
Temperature Coefficient	0.005
Inverter Efficiency	0.94
Power Conditioning Losses	0.05
Latitude	53.4
Azimuth	0.1
Tilt	30

Table 5.5: Variables input into Duffie & Beckman Hourly Model

A variation in yield is caused by the correction factor of the calculation, visible in the plot as a series of lines. This is because of the correction factors dependence on declination as an input variable, which changes daily. The prediction of the model is 1,252kWh, accurate to within 2% of the measured total of 1,279kWh. The rule of thumb used in the SAP is that 750kWh can be harvested per kWp of installed photovoltaic capacity. This would place the output of the subject system at 1,148kWh per annum, slightly less than that predicted by the model and implied by this set of measured data.

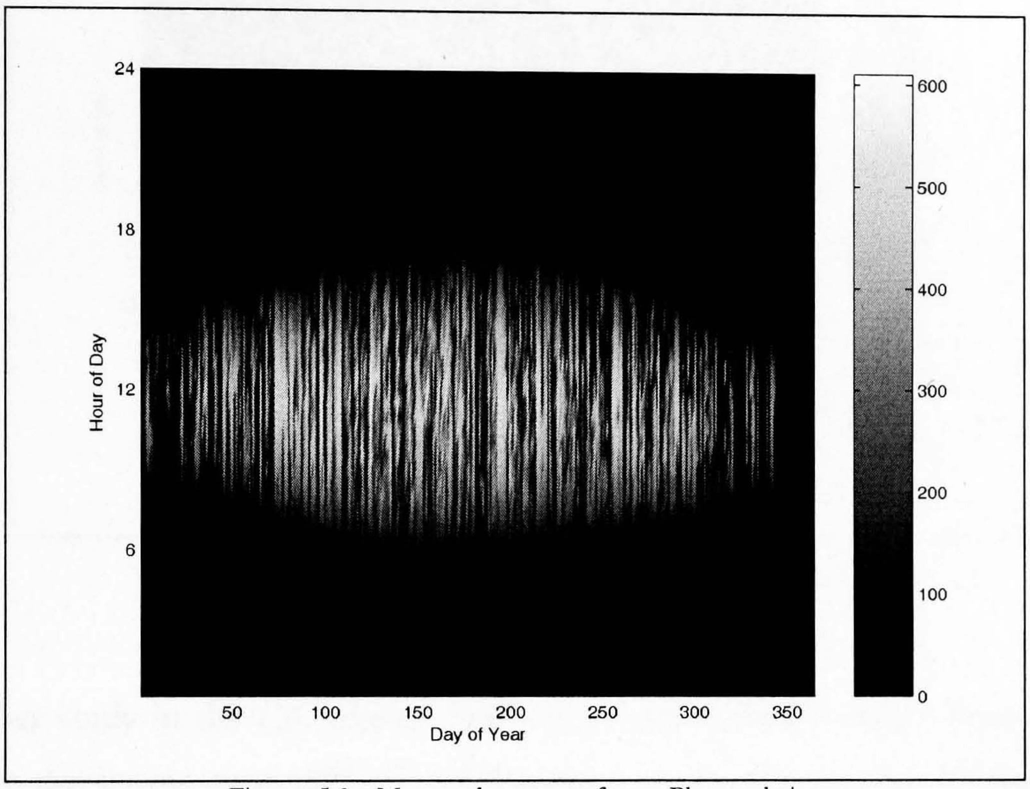


Figure 5.3: Measured output from Photovoltaic system, Nottingham for 2003. (Wh) Half hourly values

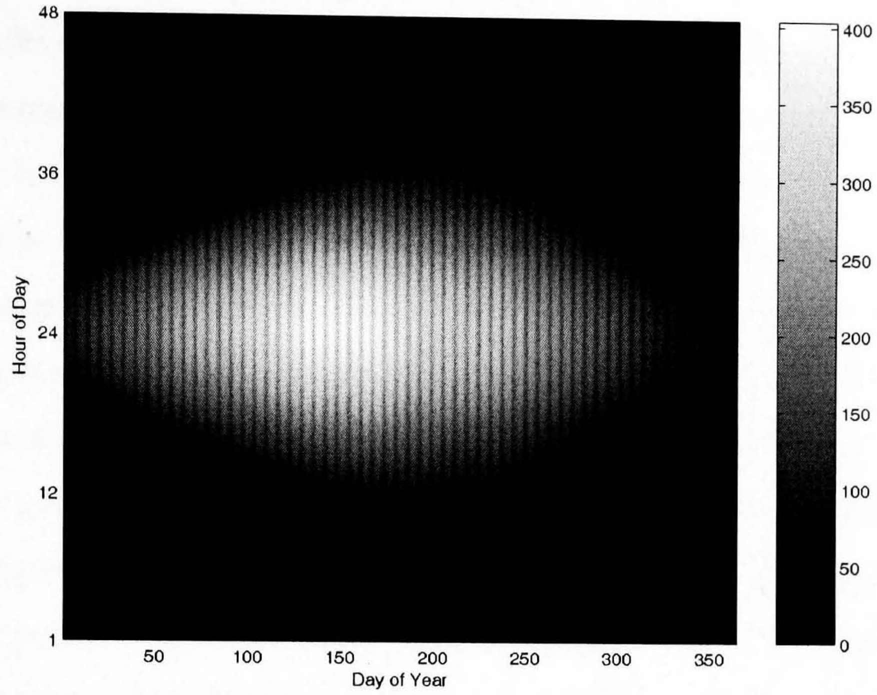


Figure 5.4: Calculated output for Photovoltaic system, Nottingham. (Wh) Half hourly values.

Another study in the UK reports yield on an annual and monthly basis rather than in the shorter term. (ETSU, 2003) reports on the data measured from eight domestic grid connected photovoltaic installations on a monthly basis. The report found simulation results based upon the system specifications to be high in comparison with the measured data, implying that losses due to soiling and inverter efficiency were underestimated. A higher temperature for the building integrated cells was also expected to be a cause of lower performance. The report does not give specific details of the installations but gives kWp, the general location, and construction characteristics of each system (Table 5.6).

Specifications of several systems were inferred from the description given in the ETSU document, selecting the cells descriptions extant in the SANDIA database with the closest match to values given in the ETSU document. The equations 5.1 and 5.2 were used to derive efficiencies and temperature coefficients and the

Duffie and Beckman hourly model was run for each. Standard values for array efficiency (95%) and inverter efficiency (93%) were initially assumed for all systems. Some of the ETSU measured data is incomplete and different time spans are measured for different systems. Data for some systems was so incomplete as to prevent comparison. To allow for comparison of the data with this study, composite years were created by substituting months from previous or subsequent years to fill gaps in data. The weather varies significantly from year to year, so these composite years are not representative of long term performance and give a guideline only. Because of this, and the incomplete information on system components, the more complete set of data from the Nottingham area is used as the primary source to validate against, whereas the ETSU figures are used as an illustration of how location, system size and other factors might affect yield. Measured data from the year 2002 was used in each case where possible, as this year had the most complete dataset for each system.

System Reference	*Region*	*System Size (kWp)*	*Module Details*
A	South West England	1.27	50Wp and 34Wp amorphous silicon laminates
B	West of England	3.43	12Wp crystalline silicon roof tiles
C	South East England	2.88	120Wp crystalline silicon modules
D	South East England	2.2	110Wp crystalline silicon modules
E	West of England	1.05	75Wp crystalline silicon modules
F	West Midlands	1.02	85Wp crystalline silicon modules
G	North West England	1.4	35Wp crystalline silicon roof tiles
H	North of England	0.68	85Wp crystalline silicon modules

Table 5.6: System Details (ETSU, 2003)

Table 5.7 shows the system specifications assumed, the modelled annual yield, and the measured annual yield of each system as given in the ETSU document. The results show a general overestimation of annual yield on the part of the model, by 20% on average. This matches with the findings of the ETSU study that simulations tended to predict higher compared to measured energy yield.

The ETSU study found that systems with inverter/array ratios of less than 0.75 suffered serious impediments to efficiency, reaching saturation at high irradiation. The optimum inverter/array ratio is given as 0.7-0.8. Operation at below 10% of the rated capacity can also reduce the performance of the inverter significantly. The study also raised the possibility that solar cells designed to integrate into the roof as tiles may suffer in terms of cooling, reducing their efficiency. The seemingly low efficiency of the systems was also attributed to soiling and shading of the cells, both of which were found to be common in long term use.

System Letter (ETSU Document)	*B*	*C*	*D*	*E*	*F*
Product	Siemens SM10	BP Solar BP5130	AstroPower AP-110	Siemens SP75 (12V)	BP Solar BP585
Overall Area	34.32	23.4	17.4	8.9	7.56
Module Efficiency	0.084	0.123	0.113	0.118	0.135
NOCT	45	47	45	45	47
Temperature Coefficient	0.0004	0.0006	0.0006	0.0006	0.0005
Degree Day Region	7	2	2	7	7
Measured Annual Yield (kWh/annum)	2073	1709	1176	630	861
Modelled Annual Yield, Duffie and Beckman Methodology (kWh/annum)	2351	2280	1558	857	857
Modelled Annual Yield, SAP Methodology (kWh/annum)	2572	2160	1650	787.5	765

Table 5.7: System specifications assumed and modelling results versus measured results

5.5 Use of the Model and Selecting Supporting Data

Following the selection of an hourly model for estimating PV yield, there are important guidelines to follow as to its use. As covered previously, recent research has indicated that important issues in the performance of PV systems are not usually represented in hourly models. The input variables and also the factors used to describe these new considerations are to be specified here.

Guidance on several issues in sizing of components and expected electrical yield was taken from the ETSU documentation of measured PV systems. The sizing of the inverter should correspond to a proportion of 70-80% of the peak output. The usual inverter efficiency of 95% can be chosen. The maximum power point efficiency and temperature coefficient are calculated from the specifications for maximum power point current, voltage and open circuit temperature coefficient.

The RETScreen planning software uses a similar model to Duffie and Beckman, with factors accounting for soiling of the cells and for inverter efficiency. The inverter efficiency is treated as constant in the RETScreen methodology and assumed not to be affected unduly by sizing issues. On the other hand, measured data suggests that inverter sizing plays a prominent role in determining the performance of a PV system, and that in many existing systems the inverter is undersized. A term to account for inverter under sizing in an hourly PV system model would look something like the following.

$$Size_{System} = \frac{P_{inv}}{P_{Array,STC}}$$ (Equation 5.17)

$$YF_i = \frac{E_{Array,i}}{E_{Array,Peak}}$$ (Equation 5.18)

$$if\left(YF_i > Size_{System}, E_{Array,i} = E_{Array,YF}\right)$$ (Equation 5.19)

Where:

YF_i is the AC yield factor for time step i
P_{inv} is the rated inverter power
$P_{Array,STC}$ is the rated power of the array at standard test conditions
$E_{Array,i}$ is the yield of the array for time step i
$E_{Array,Peak}$ is the peak yield of the array
$E_{Array,YF}$ is the output of the array given inverter saturation
$Size_{System}$ is the sizing of the system

This extra term would simulate saturation of the inverter at higher irradiances and give a more realistic estimation of the performance of a system with an undersized inverter. However, when expressed as an hourly or half hourly average the yield factor does not exceed the system sizing and this level of detail is lost. As an alternative the factor for inverter efficiency was modified to include the effect of under sizing. By default the system may be assumed to be well sized, however if the inverter size is under 70% of the peak power of the array, a penalty is applied to the inverter efficiency. The five minute timescale measured data from the Nottingham area was used to derive this penalty. A range of inverter sizes was taken and saturation was assumed to occur above the peak power of the inverter. The resulting plot of diminished output resulting from inverter saturation versus system size is given in Figure 5.5.

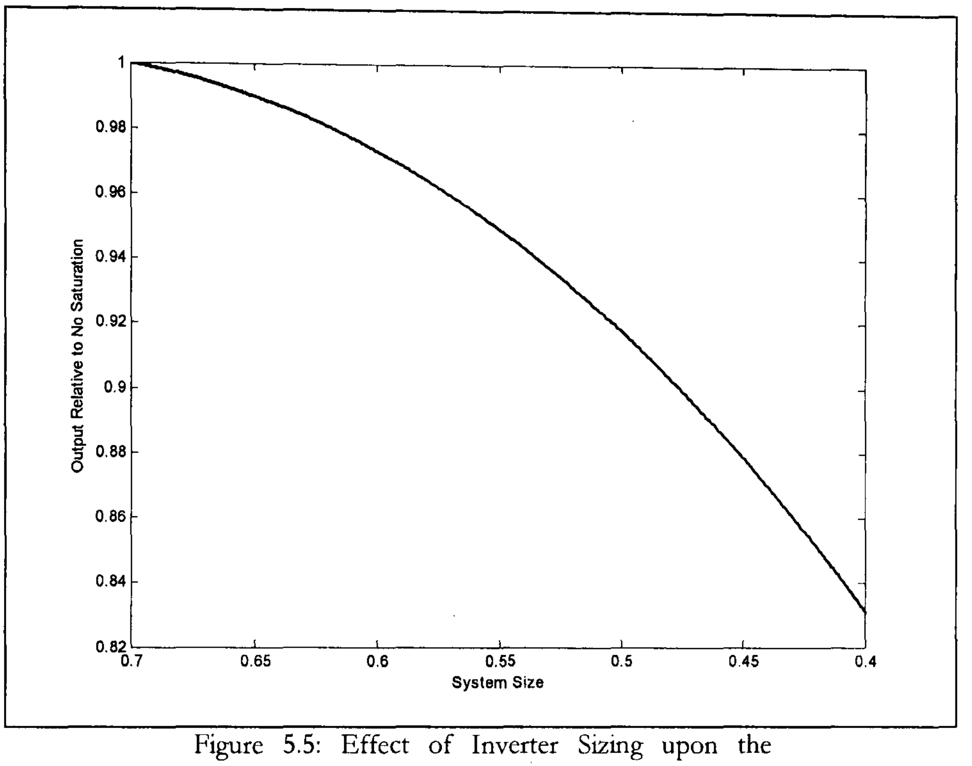


Figure 5.5: Effect of Inverter Sizing upon the Annual PV Yield

From the results, the overall effect of under sizing an inverter compared to the recommended minimum 70% of array size can be expressed as:

$$OF = 1.6Size_{System}^{3} - 3.9Size_{System}^{2} + 3.3Size_{System} + 0.014 \quad \text{(Equation 5.20)}$$

Where

OF is the output factor to multiply against the annual output of the system

$Size_{System}$ is the sizing of the system

This should not be applied to the individual hourly figures for output but could be used in the assessment of annual yield. The effect of applying this extra term to the annual yields of systems B and E, the two systems with inverters rated at less than 70% of peak array power (Table 5.8).

System Letter (ETSU Document)	*B*	*E*
Modelled Annual Yield with Cell Soiling Effect (kWh/annum)	2131	777
Measured Annual Yield (kWh/annum)	2073	630
Modelled Annual Yield with Inverter Saturation Effect (kWh/annum)	2037	620

Table 5.8: Revised Calculated Figures Compared to Measured

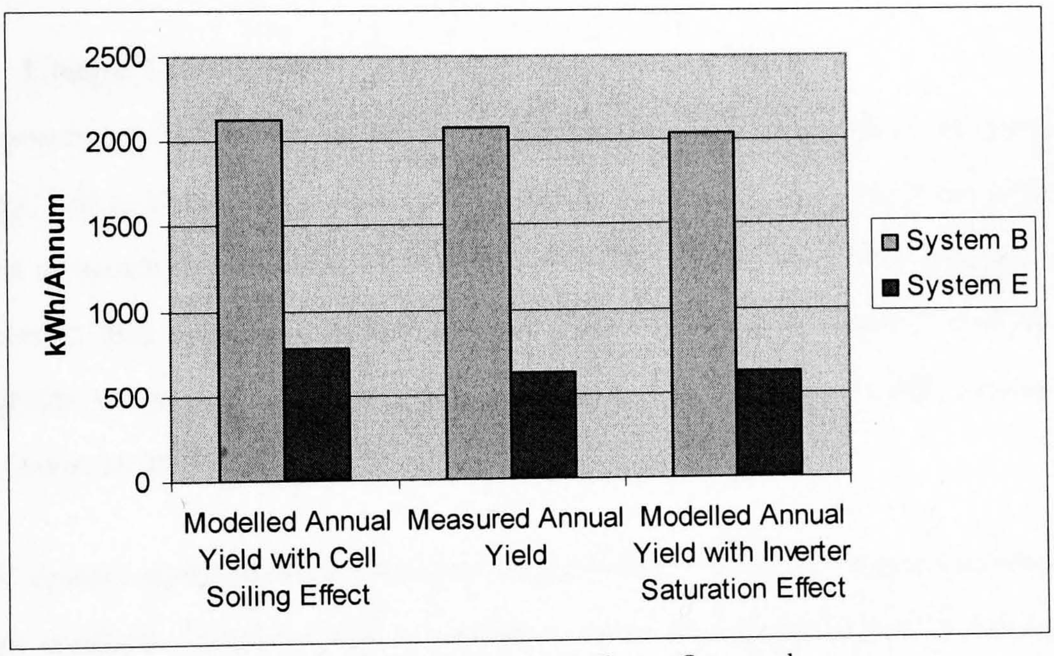


Figure 5.6: Revised Calculated Figures Compared to Measured

The ETSU study also found shading and soiling to be an issue in the measured performance of PV systems. Accounting for the effect of shading on an hourly basis is outside the scope of this study as it involves data collection on the positioning and size of potential obstacles. This level of data collection could not feasibly be done in a HER survey. A factor to account for shading could however be added to the annual yield, however it is known to be difficult to predict when shading can occur. Shading caused a reduction in efficiency between 3-10%. The ETSU study suggests that Soiling can be assumed to degrade the performance of the array in general so a fixed factor can be used also in hourly calculations. Given the findings of the ETSU report on domestic PV installations, and the RETScreen default value, the usual factor for soiling of cells is taken as 3%.

The battery efficiency and usefulness can be estimated on a monthly basis in the case of standalone systems. Effects of battery storage are outside the scope of this study and the monthly utilisation method presented in Duffie and Beckman can be used without difficulty.

5.6 Chapter Summary

PV systems rank highly in the public consciousness as symbols of renewable energy, but in practice they are very expensive to install. Income from export of excess generation can help to pay back the investment, make PV systems more economic, and therefore more popular. Under the constraints of a HER, it is important to give an accurate representation of the expected performance of a PV system so as not to mislead potential installers.

A PV system comprises of a few key components which can be represented in a design method. However the dependency upon incident irradiation has a more linear character than SDWH, giving the efficiency of the solar array the major influence upon a grid connected system. The efficiency specification of PV arrays can be measured quite accurately and specification of array performance can be sourced directly from the manufacturer, or from an online database. However, measurement of domestic PV systems in the UK climate has been quite restricted until now. Recent studies from ETSU show that problems in PV installations are common and that modelled efficiencies are rarely reached.

A leading design method model as proposed by Duffie and Beckman was chosen as a basis for representing PV systems. However, design methods for this technology tend to represent balance of system components and degradations of array performance as factors, leaving them to the judgement of the modeller. An issue in this study was to determine what factors might be considered to be reasonable in the context of the experience across the UK so far. Although the set of data available for comparison was relatively small, several issues with installations had been highlighted: inverter sizing was an important issue and shading and soiling had a greater influence over the efficiency of the systems than might previously have been expected.

To address the issues raised by the ETSU and Ransome and Funtan studies, default factors were established to represent shading, soiling of the array, and components of the model. The end result is a model adapted to represent the UK climate and sufficiently detailed to investigate the effects of PV supply and domestic demand profiles at the hourly level.

CHAPTER 6: MICRO-COMBINED HEAT AND POWER

6.1 Introduction

A μ-CHP unit is a boiler in a domestic house that simultaneously generates space and water heating and electricity. Such a technology can be retrofitted in place of an existing gas boiler, provided the dwelling has both a natural gas supply and is connected to the electricity grid. The unit acts in a similar way to a standard gas boiler, but produces heat energy with an electrical by-product. As the production is geared primarily to meet demand for space and water heating, the electricity generation is a by-product and will sometimes mismatch the dwelling's overall electricity demand.

There is a great opportunity for implementation of μ-CHP in the UK. Because it is a retrofit technology, and can directly replace aging gas boilers, there is a ready market. Although it is not a zero carbon technology, it is an emerging technology with great potential for reducing CO_2 emissions in the UK domestic energy sector (EST, 2005). μ-CHP could displace between 574kg and 892kg more CO_2 per annum than a gas condensing boiler (Peacock and Newborough, 2005). Alongside truly renewable energy technologies, it should prove important in helping the UK to fulfil its carbon emissions reduction obligation. It has been estimated that 1,000,000 μ-CHP units could be sold in the UK within the next 10-20 years given the right market conditions (Harrison, 2004). The UK government also has targets to achieve 10 GWe of CHP capacity by 2010, including μ-CHP (DTI, 2003).

There are many ways in which the unit can help to displace CO_2. There is the displacement of electrical load on the network that wider take up of the technology would cause, the reduction of losses associated with transporting electricity from centralised generation, and μ-CHP is also thought to replace more marginal electricity units generated by coal and gas directly rather than the base load units generated by nuclear or wind. A higher proportion of the gross calorific value of fuel is turned to heat than in a coal or gas powered station. The electricity that is generated goes towards meeting electrical demand in the home. The remainder, exported to the grid, helps to pay back the high purchase cost of the new unit.

Although the concept of μ-CHP suggests a number of advantages, it is a young technology not widely studied in operation. Estimates as to potential installed base, production capacity, and economic performance are necessarily provisional. Some authors question the economic and CO_2 saving viability of μ-CHP under a number of operating conditions e.g. (Hawkes and Leach, 2005), (Boait, 2006). The early results of field trials do not accord the same performance to μ-CHP units in practice as do previous estimates (The Carbon Trust, 2005). Established design method approaches are not available for estimating potential performance. To consider the potential impact of μ-CHP on a HER compared to other more established technologies, there is a need to develop a new simplified estimation of μ-CHP operation appropriate for use within a HER. There is also a need to generate awareness of the limitations of such a model, given the current uncertainties as to μ-CHP operation in practice.

6.2 Principles of μ-CHP Operation: Stirling Engine

The Stirling engine is the first technology to be sold on the market as a μ-CHP unit. The Stirling engine is an external combustion technology, whereby heat causes a working fluid to expand in a chamber and move a piston. Several such chambers and pistons can be arranged to ensure smooth transfer of power and to minimise vibration. Stirling engines have no internal burning chamber and relatively few moving parts. This reduces noise and the need for maintenance. Because the burner is external, combustion is very complete and emissions are low. Alternative fuels can be used with Stirling engine technology, so this could help to facilitate a transition toward biofuels and take the technology to zero carbon emissions status in the future, given the foundation of an installed base of fossil-fuelled units. All of these features make the technology quite suitable for implementation on the domestic market.

Stirling engines have an electrical efficiency of about 12-14% (Godin, 2005). Because the heating efficiency is higher, it is more useful to base the operation of the unit on heat rather than electrical demand. Due to this heat led nature, μ-CHP is seen as most economic for use in dwellings with a greater heating load. Solid Oxide Fuel Cells (SOFCs) are competitors to Stirling engine technology, but Stirling engine units are used as the basis for this study given their earlier presence on the market, and apparent better suitability for the UK housing stock.

6.2.1 The Whispergen Unit

The first Stirling Engine system on the UK market is the Whispergen produced by Whispertech Ltd, and supplied in the UK by E.ON Powergen (Whispergen, 2003). The Whispertech unit has four chambers and pistons connected with a patented 'wobble yoke' system to drive an alternator from their motion. This unit may operate on a timer or continuously, generating space and water heating and a corresponding proportion of electricity. It steps up the thermal output as required, activated by either the thermostat or a manual boost switch. There are a number of levels of generation capability, allowing for fine control of heat and electricity generation to offer the best efficiency. An additional auxiliary heater is incorporated into the unit, which consumes excess electrical output to augment the gas heater at times of greatest heating demand. The unit has five levels of operation (Table 6.1).

Mode	*Watts Electricity*	*kW Thermal*	*Additional*
1	400	4.9	
2	850	6.0	
3	1200	8.0	
4	1200	8.0	Aux. heater
5	1200	8.0	Aux. heater and dump

Table 6.1: Whispergen AC Mk.4 Power Outputs (Whispertech, 2003)

The unit switches operating modes according to heating load, controlled by a programmable intelligent controller (PIC). The controller logic is used to maintain the operation of the unit at its highest efficiency given the internal temperature of the dwelling. The heat demand switch is in the heating period schedules. As with other central heating controllers the heat demand schedule can be temporarily overridden for extra heating and the set point can be controlled.

6.3 Exported Electricity and Economic Viability

μ-CHP has a higher installation cost than a conventional condensing boiler, and payment for electricity exports can help to repay this cost. Recent studies have estimated that it could take tens of years to pay back the installation costs of a μ-CHP unit, emphasising the importance of export tariffs to economic viability (Peacock, 2004). Electricity export is also important in estimating the carbon displacing potential of the technology overall. Given that a HER needs to supply information to a number of parties there are different ways of counting the value of exported electricity. There is a direct displacement of import value and an economic export value to the customer, a wholesale purchase value to the supplier, and there is an absolute carbon saving value in environmental terms that could be of interest to each party.

The standard or off peak tariff that the customer pays for electricity masks the variations in the spot price. In theory, μ-CHP technology offers several advantages to the electricity supplier. Load is offset at the point of use by the electricity generation, and any export can be supplied to neighbouring dwellings. Output is expected to occur at the times of peak demand and offset the costliest of wholesale electricity. The regulation of microgeneration agreements has recently been reviewed by the government (Microgeneration Review, 2006), but suppliers are not yet obliged to offer any set recompense for export. Tariffs vary by supplier but a fixed 7p/kWh of imported electricity and 3p/kWh for export is common, as given in (BRE, 2006). Under these conditions, a domestic microgenerator is expected to rely on displacement of imports rather than on exports for payback. The alternative arrangement called net metering has an equal tariff for import and export, regardless of the time of day. This can be advantageous for the domestic exporter but is not popular with electricity suppliers because it can reduce their profit margin.

Electricity companies often use profile settlement to associate metered consumption with the half-hourly periods used for wholesale prices. This assumes a particular daily profile of demand to match with the customer's monthly consumption when half-hourly metering is not available. A more detailed estimation of μ-CHP export according to profiles of electricity consumption and heating requirements would offer a better comparison against basic templates of supply and demand and would give reasonable estimates according to dwelling and occupancy type. This highlights the disparity between charges and actual electricity export and informs as to the suitability of some dwellings for μ-CHP.

6.4 Creating a Simple Model for μ-CHP

A μ-CHP generation and export profile is required for comparison against those of other LZC technologies. To determine the export profile, profiles for thermal demand and electrical demand in the dwelling are needed. The thermal demand is calculated here using a simple heat balance adapted from the BREDEM-12 algorithms. The electrical demand is calculated using an adaptation of a model for estimating the load on distribution networks.

Using thermal and electrical demand profiles, the heating levels the unit will use to meet the heat demand are estimated and a profile of electricity production and export is generated. The export is simply expressed as:

$$E_{Annual} = \sum_{day=1}^{365} \sum_{\min=1}^{1440} Gen_{day,\min} - Demand_{day,\min}, Gen_{day,\min} > Demand_{day,\min}$$

(Equation 6.1)

Where:

E_{Annual} is the annual electrical export from μ-CHP

$Gen_{Day,Min}$ is the electrical generation from the unit for the minute of the day

$Demand_{Day,Min}$ is the electrical demand for the minute of the day

Using this method there is no assumed penalty for absorption of electricity to the grid and the power output is AC so no inverter losses are involved.

6.4.1 Heating Demand

The simplest way to estimate domestic heating demand is to make a steady state reckoning of the energy needed to keep the internal temperature of the dwelling at the set point during heating periods. Calculations of the specific heat loss – the rate of loss of heat from the dwelling through the fabric and ventilation, and the thermal gains from inside the dwelling are used to determine the energy required to maintain the house at a comfortable temperature through the heating season. BREDEM-12 gives a figure for specific losses comprising of fabric and ventilation losses, calculated from the elements of which the building is constructed, and calculates incidental gains from occupancy factors. The losses are expressed as a constant term through the day, including factors such as manual ventilation in the calculation. Wind speed and exposure factors are included in the calculation so it is particular to the location of the dwelling.

BREDEM-12 calculates the heating demand of the dwelling through use of the temperature-time graph. This is an estimation of how quickly the temperature in the dwelling will revert to background temperature after the timer switches the heating off. From this estimation for a day a mean internal temperature is derived for the dwelling for each month. BREDEM-12 is a two zone model, which separates the dwelling into a main cooking and living area, and a less well heated secondary area. It does not allow for calculating the thermal characteristics of individual rooms as in a multizone model such as ESP-r (ESRU, 2006).

In the case of the Whispergen unit, the control scheme is available in the logic of the PIC (Table 6.2). The control scheme uses intermediate heating settings to regulate the temperature on a short-term basis, according to the temperature as reported by the thermostat. This has the potential to affect the electrical output level of μ-CHP on a seasonal and even a minute by minute basis. However, the performance of a unit on such a timescale is very much particular to the construction of the dwelling and detailed simulation would offer the best accuracy at this kind of resolution. Boait et al. (2006) used an intermediate technique whereby the short term performance of a μ-CHP unit was estimated using a model of its control logic. They calculated specific loss and heat capacity for several key dwelling types, and simulated the operation of the unit given a profile of the external temperature. The results were found to compare well to measured data.

Mode	*Switch Point*	*Action*
A	Heat Demand ON	Whispergen and central heating pump turned ON. Power levels set to maintain constant temperature rise of 0.66 deg C per minute.
B	T=1	Auxiliary external heater switched OFF if operating (power reduced to P3)
C	T=t+2	Temperature T evaluated every 2 minutes, if T remains greater than t+2 then power reduced by one level (e.g. P3 to P2)
D	T=t+4	Power level reduced to P1 immediately.
E	T=t+8	Whispergen shutdown immediately. Whispergen will automatically start after 30 minutes if Temperature T is below t-3 AND heat demand signal is ON.
G	T=t-3	Temperature T evaluated every 9 minutes; if T remains less than t-3 then power level increased by 1 step (e.g. P2 to P3) Max power level is 3.
H	T=t-12	If temperature T is below t-12 the power level is set to 4. If after 9 minutes T remains less than t-12, the power level is set to 5.

Table 6.2: Whispergen PIC logic (Whispertech, 2003)

Clearly the BREDEM model cannot compete with detailed simulation in accuracy on a short term basis. However, DEMs generalise space heating demand considerably, and heating profiles that are too specific to the design of a dwelling or heater model could bias the generalisation made from them. For this reason a simpler option of estimating generic profiles according to the timer schedule and external temperature was chosen. The method can be used to predict a typical profile of space heating load according to the timer settings on the μ-CHP unit, varying by month and hour and influencing the electrical output on this timescale. This predicts the likely daily electrical performance of a generic Stirling engine μ-CHP unit rather than specifically emulating the control logic of any particular model.

A simple energy balance is used to determine the retention of heat and the heating load through the day. The specific loss is calculated using the BREDEM-12 algorithms, and then Equation 6.2 is used to determine the profile of demand for space heating within the dwelling for each hour.

$$Q_h = U_B(t_{sp} - t_a) - G_B \qquad \text{(Equation 6.2)}$$

Where

Q_h is heating input
U_B is the specific loss of the dwelling
t_{sp} is the set point temperature
t_a is ambient temperature
G_B is incidental gains

This calculation distributes the daily heating load by hour. While it gives the same overall results as the BREDEM calculations for compatibility, as the thermal performance of the μ-CHP unit is calculated in BREDEM-12 in the same way as with a normal boiler given a particular efficiency, it also gives an hourly figure for use in estimating the quantity of export. The calculation of daily average heat loss is first made on a steady state basis. Then a decrement factor as given in (CIBSE, 1986) is applied to modify the hourly heat loss following the 24 hour swing in external temperature.

From the methods described above, and from the hourly ambient temperature for each month's average day, a heat loss and gain for the dwelling can be estimated. Depending upon the reading of the thermostat and the timer setting, the unit changes its level of operation, and this can be estimated according to the rated outputs. Timer settings and set points were applied for standard occupancy and other occupancy patterns, examples of which are shown in Table 6.3.

Program	*Set Point*	*Heating Schedule*
Standard	21	2 hours morning, 7 hours evening, 16 hours continuous at the weekend
Extended	21	16 hours continuous all days of the week
Evening	21	5 hours evening
Sheltered	23	16 hours continuous all days of the week

Table 6.3: Example Heating Schedules Used in μ-CHP Case Study (NHER Software)

6.4.2 *Electricity Demand in the Dwelling*

Recent research shows the need for a minute by minute level of accuracy in accounting for μ-CHP export, as hourly average figures can be misleading (Hawkes and Leach, 2005). The space and water heating requirement can be calculated more generally as they are thermal processes the profiles for which do not change significantly in the short term. Electricity demand, however, is known to be quite variable on short timescales. The demand for lights and appliances is mostly independent of the building fabric and may be generated by stochastic means. One method for simulating electricity demand on a minute by minute basis is presented in (Stokes, et al., 2004). Although it was created for modelling of distribution network demand, it can be adapted to model electrical demand in any one dwelling. An example output profile is given in Figure 6.1.

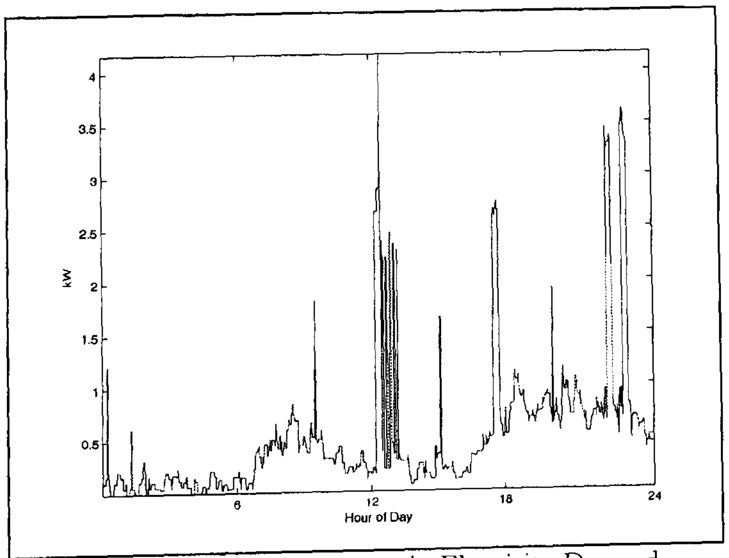


Figure 6.1: Example Domestic Electricity Demand Profile Generated Using the Stokes Model

The model can automatically allocate a list of appliances to a household on a statistical basis using the ACORN (CACI Limited, 2003) code of the area. It caters for climate and for occupant behaviour. Each component is modelled separately for modularity and flexibility. This allows changes to be made to adjust the model to demand patterns and appliances of the future. The model accounts for lighting, space and water-heating, cooking, washing, food cooling, and miscellaneous electrical demand from small appliances and standby. Modifiers are given for electricity use according to level of occupancy, income, and lifestyle category. A few modifications were made to the model for this study. Electric storage heating is not allowed as μ-CHP is assumed to replace it. The Stokes model scales the expected level of electricity usage and appliance ownership by year in order to predict expected increases in demand in future. For this study a base year of 2003 was selected, as actual data of wholesale electricity pricing was available for this year.

6.5 Case Studies

The techniques described above were applied to describe the behaviour of μ-CHP unit installed in generic building types. There is a lack of measured data on μ-CHP performance in the literature, so estimates cannot be compared to experience. This case study was performed to compare for consistency with such detailed estimates of annual μ-CHP electricity output and export as are currently available. Standard housing dimensions taken from the BEPAC definition were used (Allen, 1990). Changes were made to some of the specifications to reflect a more recent finding of housing conditions according to the English House Condition Survey (EHCS) of 2001 (EHCS, 2001), showing a higher incidence of cavity wall insulation compared to previous surveys. In addition to the elements of the dwelling required as inputs for BREDEM-12, variables representing electrical appliance ownership, occupancy, and occupant income were required to calculate an electrical demand profile. A particular roster of appliances was selected using the assigned ownership data given in the Stokes model, excluding duplication of appliances (i.e. a combination of fridge, freezer and fridge freezer), and assigned an income around the national average (Table 6.4).

The electricity generation profile is obtained as previously described. The ambient temperatures are taken from the BREDEM-12 specification as previously described, and the specific loss figure determines the heat loss. Depending upon the heating load the controller senses, it changes the level of output of the unit.

Variable	*Value*
Number Of Occupants	2
Annual Income	National Average (£20K)
Electric Storage Heaters	No
Electric Water Heating	No
Electric Hob	No
Electric Oven	No
Microwave	Yes
Kettle	Yes
Fridge	Yes
Fridge-Freezer	No
Freezer	Yes
Combined Washer/Dryer	Yes
Dishwasher	Yes

Table 6.4: Appliances present in detached dwelling case study.

In this instance a control strategy of near continuous operation is used. The duration and timing of the programmed heating schedule is likely to have a substantial effect both upon the quantity of production and of export. Runs were performed under the three heating schedules previously described, and the results are given in Table 6.5.

House Type	*Metabolic Gains*	*Lights and Appliances*	*Cooking Gains*	*Water Heating*	*Solar Gains*	*Specific Loss (W/°C)*	*Output (kWh /annum)*	*Export (%)*
Detached	120	264	68	71	288	386.6	3379	36
Semi Detached	120	213	68	71	233	266.7	3404	38
Period Terrace	120	212	68	71	178	265.6	3358	37
Bungalow	120	183	68	71	227	251.9	1752	12
Post 1919 Terrace	120	196	68	71	234	167.9	2187	46

Table 6.5: Inputs and Results of μ-CHP Case Study Runs

To test the prediction of the simplified method against the greater detail of a method using PIC emulation, a comparison was made for key dwelling types. A version of the Whispergen PIC was implemented in software, which changed modes on a shorter timescale in response to an assumed sensed indoor temperature. The heat capacity of the dwellings as given in the Boait paper was used. A continuous timer setting (permanently on) was chosen for this comparison. Averaging the results to the half hourly resolution – the minimum at which temperature data is available, the totals for annual production were as shown in Table 6.6. This shows that annual output and proportion of export can be similar in methods based upon the controller of the μ-CHP unit and those based upon overall heat loss. Steady state calculations are known to give reasonably accurate results if detailed simulation is not required, but finding the proportion of electricity export to be similar is an interesting finding. However, this does not confirm that the timing of the export is the same using the two methodologies.

Method	*kWh$_e$/annum*	*Electrical Output Exported*
PIC Emulation	3285	51%
Specific Loss Only	3375	53%

Table 6.6: Comparison of μ-CHP kWhe annual output and proportion of export, detailed and simple methodologies, detached house

Although there is a lack of published measured data on μ-CHP performance, there are a number of publications estimating the effect of greater diffusion of the technology in the UK, and the likely economic consequences of uptake. The estimates are diverse because of the variety of dwelling types and occupancy profiles to choose from. Nonetheless the available literature points towards a particular range of values.

Peacock (2004) estimated the performance of a 1kW Stirling Engine μ-CHP unit, estimating that 75% of electrical demand was imported, with an import of 4334 kWh and export of 986, giving 2430kWh/annum in generation. Hawkes and Leach (2005) place the electrical output of a 1kW Stirling engine μ-CHP unit from just below 2000kWh/annum to just below 3000kWh/annum. Boait et al. (2006) give estimates for between 1760 kWh/annum for a terrace and 3372 kWh/annum for a detached house, with validation against the output of an existing μ-CHP unit. The results of the case studies performed here fall within the range of estimates made in the literature.

In terms of export, the Hawkes and Leach paper estimates that about 25% of generation is exported in each case based upon identical heat demand patterns. Boait gives an export of around 40% with high occupancy and 60% with low occupancy, through all the main housing types. Peacock estimates an export of approximately 40%, given realistic profiles for heating and electricity. The proportion of export as calculated by the model in this chapter is in the range 12-

46%, but this does not necessarily cover the same dwelling types and occupancies in the same way as do the other studies.

The results presented in this chapter could be negated by short-term heating demands that are only revealed by simulation and measured data from various house types. Validation against other research has gone some way to addressing the possibility of accuracy problems and towards suggesting that this method can give credible results on a more general level. However, this can only be proven upon the publication of DTI field trial data, the data of which were being analysed at the time of writing, and this method is presented as a way to gain a simple and general accounting of μ-CHP production, and the timing and proportion of export that might be expected.

6.6 Chapter Summary

μ-CHP technology has the potential to become a strong feature in the national effort to reduce carbon emissions. Units can be retrofitted in place of an existing gas boiler, offering the displacement of electricity consumed in the home and export of the excess to the grid. This could help in paying back the cost of installation, which is significantly higher than a standard replacement boiler. μ-CHP is new to the market and published measured data on its performance is not widely available. There is some uncertainty over the performance and export capability of μ-CHP in field conditions. To calculate the potential export over short time steps, models for electrical demand and heating are needed. These demand profiles can be subject to complex influences and variation that needs to be generalised for use in a HER.

Prior calculations of specific loss for the building, as made using the BREDEM-12 model, give a figure for average gains and losses for each month. A steady state calculation is made with allocation of 24 hour swings in temperature for heating load as in the CIBSE admittance method. The heating programmer times determine when the unit is operational. The Stirling engine μ-CHP unit has several modes of heating so a set level of operation can be given for each half-hourly time step. The internal control scheme of the unit was not used in the modelling beyond the determination of the overall output levels, which match the heating demand at each time step. Electricity demand, however, is obtained through a stochastic method, giving a profile that fits the type of dwelling and specified occupants. This is generated on a minute by minute timescale so it offers a greater granularity.

This technique estimated electrical output in the region of 2-3MWh for μ-CHP depending upon dwelling type. This corresponds well with the range calculated by the available literature. However, the accuracy of the figures for export is less clear. Sources estimate the proportion of generated electricity exported from 15% to 60%. While a similar range of exports is covered by the methodology as described, it does not relate directly to the same building types and occupancy patterns. Given the current unavailability of measured data, this methodology is taken as the best compromise approach for the available data.

CHAPTER 7: DISTRIBUTED GENERATION AND EXPORT TO GRID

7.1 Introduction

Placing a value on energy exported to the grid is a difficult thing to do. In the case of exporting microgeneration technologies a value needs to be placed on the potential electricity export in addition to the generated electricity used in the home. This can be difficult to do in the current cost based context of HERs, because the conditions for export payment can vary between suppliers. Government incentives for export can also vary depending on the technology so the payment is not a fixed quality per unit electricity. Assigning a set payment for export is unlikely to reflect the true situation consistently in every case. Therefore there is a requirement to find a metric that can represent export consistently across LZC types.

The national supply and demand for electricity changes at each particular moment in time. Additionally, the value per kWh unit of electricity can be measured in a number of ways. Exporting or storing electricity will lead to losses, so it is most useful if it is utilised as it is generated in the home. If it cannot be utilised on site, exported electricity can be supplied to the distribution network and smooth the peaks in demand from the grid for neighbouring houses. This helps to offset CO_2 emissions and expensive coal and gas fired generation. Distributed generation can also contribute to base load, but peak smoothing is preferable because base load generation is supplied by the more efficient technologies.

The money cost of electricity to distributors from centralised generators is settled in a bidding system using predictions of half hourly demand for each region. However, domestic customers are charged a standard rate per unit all day. This means that at some times during the day distributors overcharge, at others they undercharge. If a domestic dwelling exports electricity, the exporter will usually be paid an agreed standard rate per unit. Because of the changing price of wholesale electricity through the day, the exporter may not be paid a sum commensurate to the value of the electricity they export. There is no set legal minimum tariff to pay for export to grid and the actual tariffs paid can vary significantly across the country. Given the changeable spot wholesale prices, this makes it difficult to offer a useable and consistent metric by which to compare the value of electricity export. An alternative metric is offered in the CO_2 emissions displaced by exported electricity, which is a useful indicator for the efficiency, timing and quantity of generation. Although obtaining an instantaneous measurement of emissions displaced from the grid is impossible, a reasonable estimation can be made at the half hourly level.

If the half-hourly variation in supply of LZC technologies is considered against the potential CO_2 emissions displaced, a view on their relative effectiveness in these terms can be gained. From this, a judgement on suitable combinations of renewable and carbon reducing technologies may be formed for particular dwellings and situations.

7.2 Choosing a Metric

There are a number of ways to measure the quality of electricity supplied to the consumer. Electricity has the elements of quantity and timing to consider in estimating both its usefulness to the end user and difficulty to supply. The source and efficiency of electricity production also comes into play when considering environmental implications. The amount of pollution per unit depends upon the generation technology. Metrics for the usefulness of electricity can take on a further political dimension by predicting the incentives in place for low carbon energy generation. These factors can all be represented in the cost of electricity or be used to derive the rating directly if they are seen to be informative.

The present way of measuring the usefulness of electricity is in quantity and cost. UK businesses usually charge a single tariff per kWh regardless of timing; although a dual rate tariff (Economy 7) is also available, reflecting the cheaper cost of generating at specific periods. The sophisticated barter system for settling wholesale electricity prices among the distributor network counts the monetary cost of generation but not the environmental cost. A number of metrics can be applied to electricity export besides its monetary value. The cost metric can be modified in several ways to reflect the price to the generator or the distributor.

7.2.1 Monetary Value

In the UK at the time of writing, for a single rate electricity tariff the consumer will pay about 7p/kWh, and an electricity exporter may be offered about 3p/kWh at 2006 prices (BRE, 2006). This does not reflect the reality of electricity generation because wholesale prices vary through the day.

It is known that the spot price of electricity can have a significant effect on the viability of renewable energy. For example, in (Meyer, 2004) a measured hourly average profile of PV export in Germany over the year 2001 was compared with wholesale prices on the Amsterdam Power Exchange (APX) and the European Power Exchange (EEX). The study found that the financial value of units of PV electricity was increased by 17% for the EEX and by 63% on the APX, when calculated with hourly wholesale figures, instead of a fixed tariff. These results are interesting but cannot be directly compared with pricing under the UK's NETA, where the bidding system strongly penalises any intermittency of supply (Bathurst, 2001). The NETA arrangement (Elexon, 2004) in the UK determines supply prices using a barter system for each half-hour (Figure 7.1). Companies bid to supply or receive and distribute electricity, and are penalised if they fail to honour successful bids. Their bids are based upon algorithms for comparing consumer's aggregate electricity demand to the combination of generation plant that can meet the demand for each half hour. Customer demand through the day can be estimated according to a generic profile (Figure 7.2). This profile would be different for dwellings equipped with LZC technologies, reducing the load at times of peak demand.

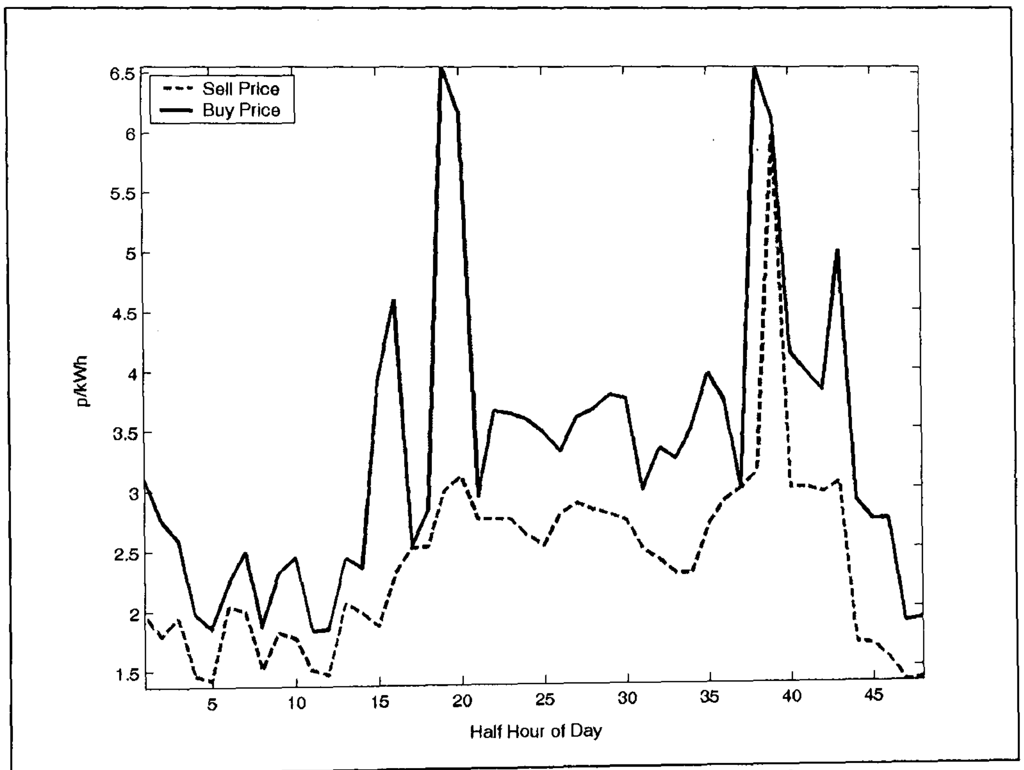


Figure 7.1: NETA Settlement Prices Example (29/1/2004)

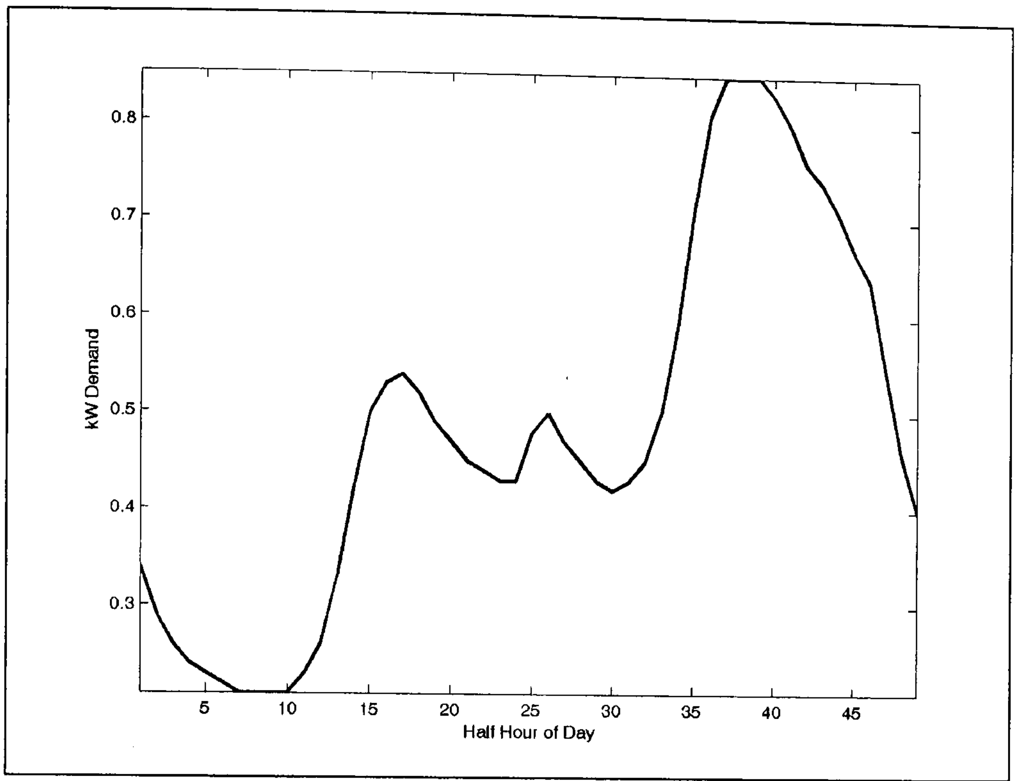


Figure 7.2: NETA Generic Domestic Demand Profile, Half Hour Average

Because half-hourly metering is rarely used in a domestic context, generic profiles are used in charging for and considering domestic demand. The difference between the actual demand profile and the assumed one will even out under consideration of greater numbers of consumers. Neither the settlement pool price not the generic profiles of domestic electricity demand give an accurate reflection of utility of electricity to the customer. The flat p/kWh tariff as paid by the utility companies is a better reflection of the real world payment to the customer at this point in time.

7.2.2 Renewable Market Value

Jones and Underwood (2001) suggest the use of the renewable market value in their evaluation of alternative measures to establish the cost per kWh of renewable generated electricity. This means accounting for the system in the context of government incentives in place to promote low carbon energy. Such a metric requires detailed knowledge of the installation cost of the system, any temporary, ongoing, and future government incentives, and the estimated cost of electricity through the predicted lifetime of the system. This kind of valuation can be quite speculative in nature as the unknowns are many.

Although this metric is comprehensive in covering all aspects of the value of energy to the customer, it is difficult to predict conditions many years in advance. Data on cost of installation is not always readily available and is subject to short-term fluctuations in the market. There are many ways to run a cost-benefit analysis and these can offer different results depending upon the initial assumptions that are made. For these reasons, a market value metric is too contentious a measurement to use in the context of HERs, especially given the difficulty of obtaining the additional information for each rating exercise and the problems associated with making assumptions about future policy.

7.2.3 CO_2 Displacement

Electricity supplied from the mains will inevitably involve some emissions of CO_2 short of a 100% renewable generation mix. Generating electricity from LZC technologies at the point of use can help to reduce these emissions. The CO_2 emissions for a particular moment in time depend upon the demand and the proportion of the load supplied by nuclear and LZCs versus coal, gas, and oil. If export to grid generally coincides with peak load electricity it has the potential to reduce CO_2 emissions in greater measure per unit.

The mixture of gasses released by fossil fuels can be expressed as a carbon equivalent figure. Energy units of electricity are converted into equivalent CO_2 emissions using a conversion factor. The figures used in the UK carbon index calculations are shown in Table 7.1.

Fuel	*g CO_2 per MJ*
Gas (mains)	54
Electricity	115

Table 7.1: Carbon Dioxide Emission Factors for Delivered Energy (BRE, 2001)

Although the CO_2 emissions figure is variable, it is not subject to the distorting economic effects of monetary cost. Its root in the physical processes of generation gives it transparency and makes it an intuitive metric to use. It is also useful in a policy sense as it is the metric usually specified in UK environmental legislation. CO_2 emissions are not commonly quoted on a half-hourly basis because the generation mix is too complex to quantify emissions precisely. However, even a general estimation of emissions levels, if it is consistent and transparently calculated, can serve to inform the best timing for electricity export. This can therefore be a reasonable measure by which to quantify the value of electricity exported, in addition to quotation of the usual costing of electrical energy.

7.3 Estimating National CO_2 Emissions

The CO_2 emissions displaced can be a useful metric for evaluating the utility of energy on a temporal basis. Although this way of measuring the value of energy encompasses environmental issues, timing and quantity, it is usually expressed as a static figure. This is because the generation mix for the UK is so complex that that no definitive CO_2 emissions measurement can be made on a short timescale. It takes a detailed simulation considering generation ranking order, outages, and scheduled maintenance, alongside overall demand, to give a minute by minute estimate, an example of which is given in Voorspools (2000). A previous example of estimated time of day CO_2 emissions that is specific to the UK grid is given in Beggs (1996) and is calculated by forecasted bid prices for generation to estimate the ranking order. However, this estimation only covers key dates in the year for the purpose of predicting and comparing peak and minimum emissions figures at specific times of those days.

A metric for estimating the relative value of displaced electricity for each half hour can follow a simpler procedure than detailed simulation. An estimate of the half-hourly emissions can be sufficient to use in a profile for comparison. To create this estimate a profile of demand and a load duration curve of plant requirement for the year can be combined (Wright, W. 2005). The National Grid Seven Year Statement gives examples of the national generation mix for all levels of demand (Figure 7.3) (National Grid, 2004). This is adapted in this study to give an estimate of the mix for each half hour of the day. The long-term average half-hourly demand is published in the NETA settlement process (Figure 7.4), and a more detailed half hourly estimation of demand from the national grid is given in (National Grid, 2005). To estimate CO_2 emissions per kWh, a normalised profile of generation was combined with data on emissions figures for peak and minimum load, with intermediate figures interpolated. This produces a half hourly profile of the estimated generation mix for each day. Figure 7.5 illustrates the estimated generation mix for peak demand. The percentage mix of each generation technology is then related to carbon emissions using published data to produce an estimate of the carbon emissions per unit. The headroom for frequency management is drawn from coal and oil fired plant; the interconnection sourced electricity is derived from national statistics.

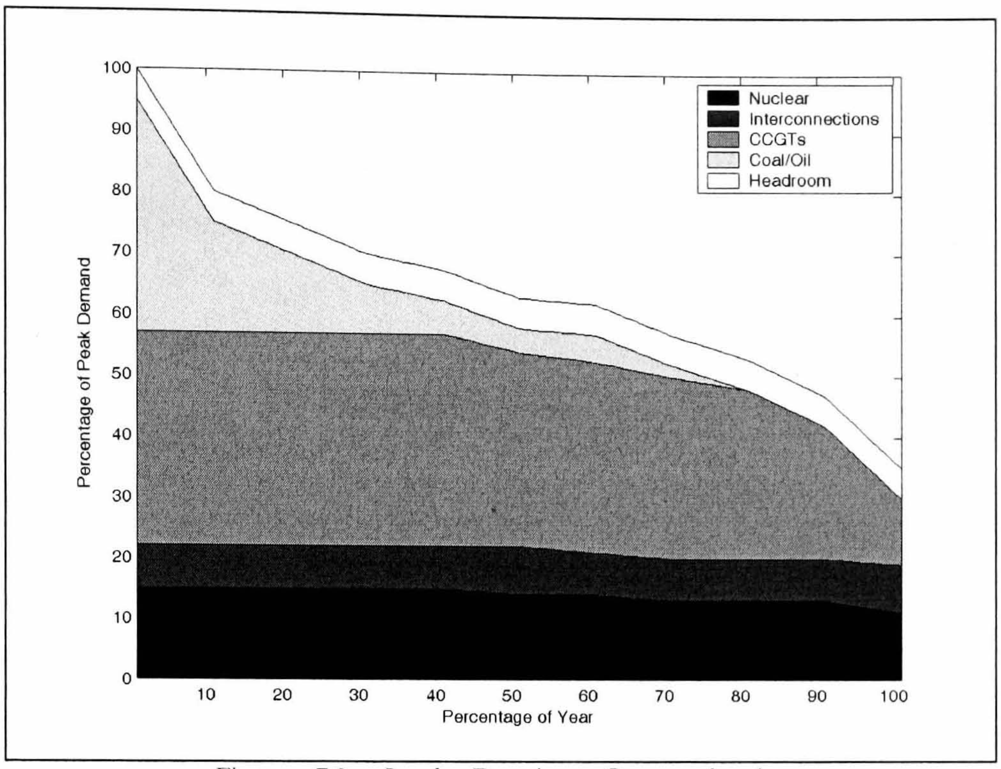
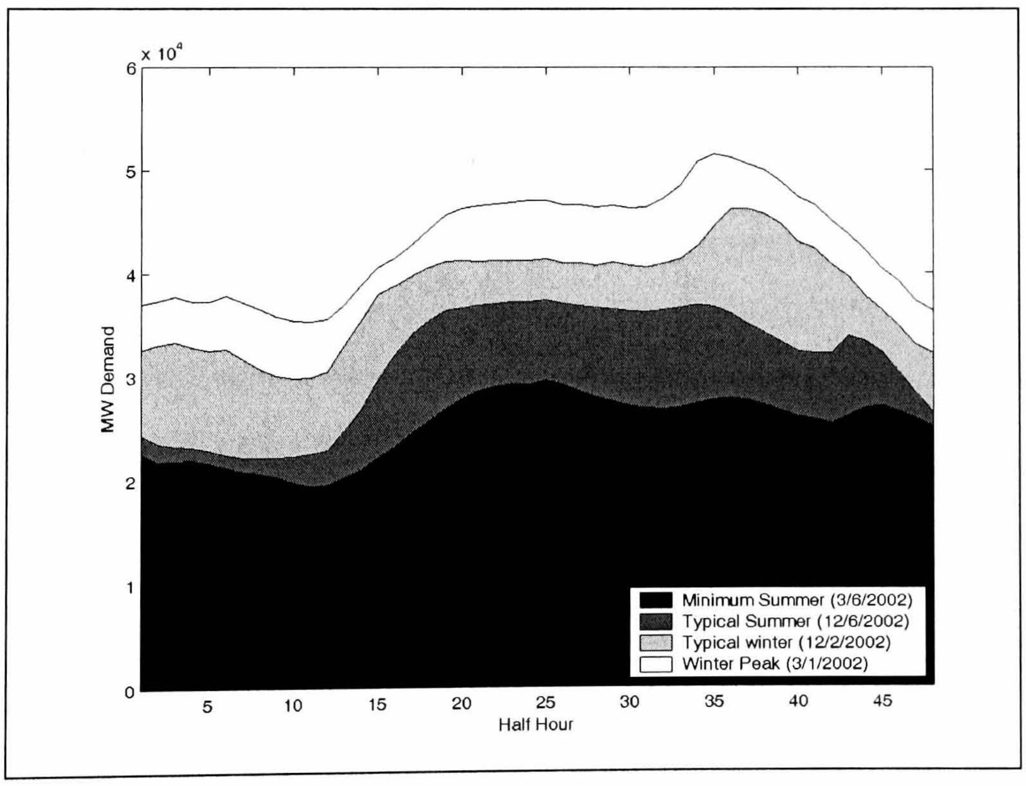


Figure 7.3: Load Duration Curve showing responsive plant requirement net of demand management (National Grid Company, 2004)[3]



[3] Note that headroom will typically be drawn from coal or oil fired plant.

Figure 7.4: Demands for key days, 2002 (National Grid, 2004)

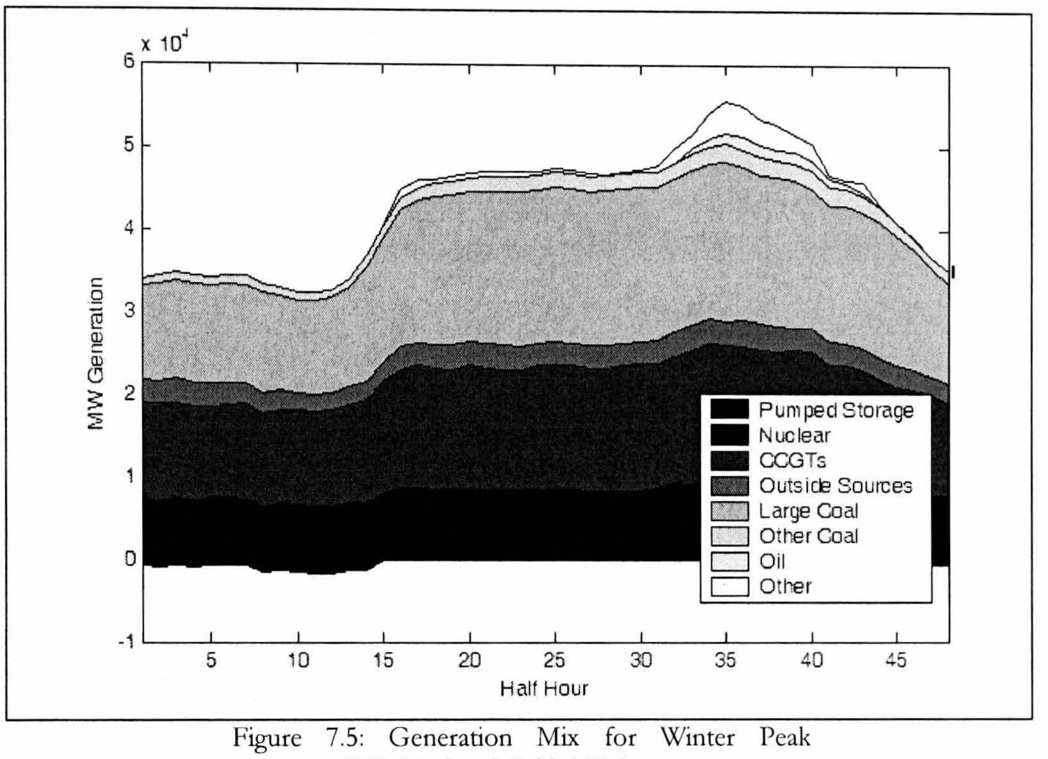


Figure 7.5: Generation Mix for Winter Peak Demand 2002 (National Grid, 2004)

7.3.1 Interconnection Sourced Electricity Mix

Energy is sourced to the English national grid from interconnections to Scotland and France. The generation mix for each is taken from published data; see Table 7.2 and Table 7.3. According to National Grid Seven Year Statement figures[4], the ratio between the two volumes of supply is France 30% Scotland 70%. Because the interconnections are used to meet base load, a stable ratio between the two is assumed and the resulting figures are given in Table 7.4.

4 Table 3.13 Constrained Generation Ranking Order of Operation

Technology	*% of Total*
Hydro	14
Nuclear	77
Conventional Thermal	9

Table 7.2: Generation Mix in France 2001 (Eurostat, 2003)

Technology	*% of Total*
Hydro	11
Nuclear	44
Conventional Thermal	45

Table 7.3: Generation Mix in Scotland 1999/2005 (Scottish Executive Publications)

Technology	*% of Total*
Hydro	12
Nuclear	54
Conventional Thermal	34

Table 7.4: Combination Generation Mix for Interconnection Supplied Electricity

An emission factor of CO_2 per GJ of energy produced can be assigned to the fossil fuel generation (Table 7.5). CO_2 emissions from nuclear, hydro, and renewable facilities are negligible.

	Natural gas	*Oil*	*Coal*
Carbon Dioxide[6]	14,000	19,000	24,000

Table 7.5: Emissions factors for stationary combustion of fossil fuels, grams/GJ (DTI, 2002a)

Oil and coal fired generation are presented together in National Grid figures. A combined figure of 21,500 g/GJ is assumed in this case. From these figures, a

5 'Other LZCs' incorporated into Hydro electricity figure for brevity.

6 Expressed in terms of weight of carbon produced.

profile of CO_2 emissions per half hour can be generated to compare to each demand profile. Figure 7.6 demonstrates how the CO_2 emissions profiles change significantly between seasons.

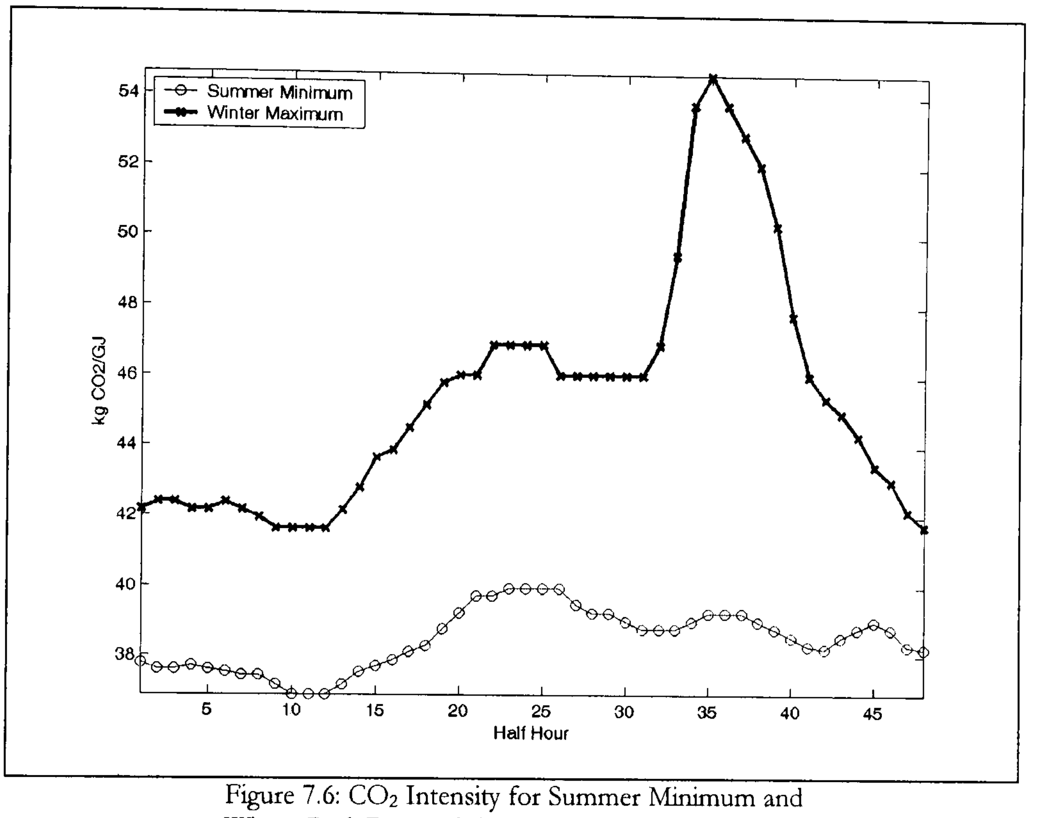


Figure 7.6: CO_2 Intensity for Summer Minimum and Winter Peak Demand Generation Mix

These profiles can be used as a standard for the utility of electricity exports at each half-hour of the day, for each day in the year. The winter peak profile varies far more than the summer minimum. Because of the comparative size of the UK's generating plant, even the small variation in the summer profile represents a significant quantity of emissions.

7.4 Choosing a Methodology for Comparison

The derivation of a half-hourly profile for the CO_2 emissions metric has been described. An explicit methodology is needed for comparing profiles of electricity use and export with the value of that export. The methodology defines the chosen timescale, how the generation profile is calculated, and how the export profile is compared against it.

Different aspects of the performance of the technology can be highlighted using different figures. Comparison can be made using either the local electricity demand met by LZC or the exported surplus versus the CO_2 emissions displaced. The likelihood is that a number of descriptive figures that are summarised in a rating will also be quoted alongside it.

7.4.1 Settlement Profiles

Standard energy load profiles are used in the UK electricity settlement system. They could be used to represent the effects of LZCs singly or in combination. The settlement system uses two profiles of domestic energy demand to estimate the load for a dwelling. These are variable for temperature, daylight hours and holiday profiles. They are modified to account for economy seven tariffs in a process known as chunking. A typical storage heater charging pattern replaces the original profile for off-peak half-hours. Chunking has also been used to account for extra off peak periods during mid afternoon. This has met with limited success according to industry opinion. The addition of renewable export to the standard settlement profiles would be a costly proposition, and is unlikely in the short term.

Two alternatives to the use of standard profiles with chunking have been put forward in (E.A. Technology, 2001). One is a solution called Reduced Data Profile representation, whereby regression equations account for a wider range of variables than the standard profiles, including: temperature, season, day of week and lighting-up time. The other is virtual metering, in which a computer model of the dwelling is run under suitable climate conditions. The resulting demand profile is used in settlement practices. This latter method gives a more accurate estimation of demand than standard settlement profiles. The application for the metric and methodology proposed in this paper is in simplified modelling of domestic energy demand and production. This too can be thought of as a virtual meter, which can be compared to the utility of energy with a load-matching factor as discussed below.

7.4.2 Load Matching Factor

A load-matching factor was applied to the German 1000 photovoltaic roofs programme to compare the measured electricity consumption of some of the dwellings (Heydenreich et al., 96). This is a shorthand way of establishing how well the generated electricity matches demand. It can be applied as a calculation of the average 'value' of energy generated by domestic LZCs. Figure 7.7 gives a visual demonstration of the load matching factor for an example PV system.

The load matching factor λ_N is defined as:

$$\lambda_N = 1 - 0.5 \cdot \int_0^T \Theta^{\Delta} dt$$

(Equation 7.1)

$$\Theta^{\Delta} = \left| \frac{P_{CONSUMPTION}(t)}{\int_0^T P_{CONSUMPTION}(\tau) d\tau} - \frac{PV_{USE}(t)}{\int_0^T PV_{USE}(\tau) d\tau} \right|$$

(Equation 7.2)

Where:

$P_{CONSUMPTION}$ is the electricity demand,

PV_{USE} is the PV generation, and

T is the 24-hour period

A maximum λ_N of one indicates a perfect match, and a minimum value of zero indicates a complete mismatch between the two profiles. This value is independent of the size of the installation. If the installation were sized to match the demand exactly then the load matching factor would represent the percentage of PV output that could be utilised directly.

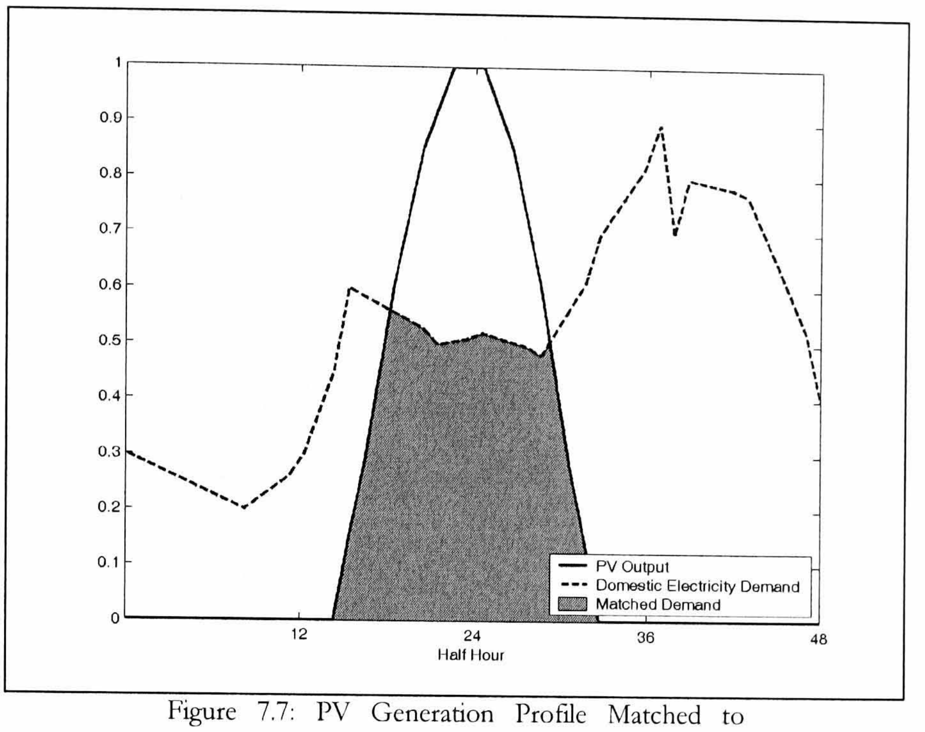


Figure 7.7: PV Generation Profile Matched to Electricity Demand Profile. The Load Matching Factor is 0.35

The usefulness of energy export depends upon the timing of its production. If a normalised daily profile charting the CO_2 displacement of electricity export for each timeslot of the day is generated and compared to LZCs production, a similar load-matching factor can be applied to it. The load matching factor then represents the usefulness of the export profile versus the demand for export.

The variation in carbon intensity through the day is comparatively small. The y-axis is rescaled as a percentage between the minimum and maximum. This is to clarify that the metric does not represent an actual measured value but the relative benefit of exports. The export utility is similarly scaled over the twenty-four hour period, as is the PV profile.

This might have a distorting effect if a one to one comparison between the two profiles were being made, however in this case it is more appropriate because of scaling factors. The UK generation pool is comparatively vast so small variations make a greater difference. Note that carbon intensity and PV generation change in winter months so the scale changes seasonally. The change in value according to the chosen metric is the important consideration in this context rather than measuring absolute carbon emissions.

7.5 Chapter Summary

The value of electricity generation is not constant through the day. The metrics that are currently used do not account for this time dependence. Many alternative metrics can be used, although each uses different criteria and is useful to a different audience. The best metric to find the value of electricity exported from a dwelling is to estimate CO_2 emissions avoided. This can be used on a half-hourly timescale as a basis for knowing when electricity is most needed by the grid. This depends upon an estimate of what the UK generation mix is for each half hour of the day.

Data about the grid can be inferred from published information of generation profiles and generation distribution curves. These are combined to give a picture of generation distribution, and a carbon intensity measurement for each half hour in the day. The profile is unlikely to be absolutely accurate but it forms a well-defined standard against which to compare. The profile is modified so that the values scale from zero to one, and is renamed the export utility.

Profiles of electricity load and export are plotted against this to give a picture of the value of LZCs over time. A load matching factor is used to compare like with like in terms of supply against domestic load. A similar procedure can be used to determine the fit of generation to the previously defined profile of export value. However, this procedure runs against a modified profile of carbon intensity rescaled from 0 to 100% on the y-axis. This results in a single figure for fit to demand for each season, which expresses a neutral value of export electricity from the dwelling.

CHAPTER 8: DERIVING SIMPLIFIED LOW OR ZERO CARBON TECHNOLOGY MODELS FOR HOME ENERGY RATINGS

8.1 Introduction

Predesign estimates of energy output from LZC technologies require calculations over small time steps, typically hourly or half-hourly. HER software and the DEMs on which they are based have traditionally avoided these kinds of calculations, favouring the greater batch processing speed and limited user input implied by much simplified models. Although the computing power that is generally available to HER software is now much improved, fine grain calculations of this kind are unlikely to be accepted by the industry in the simplified DEMs of the foreseeable future. However, apart from accuracy per se, the effects of certain aspects of LZC performance and interaction can only be observed at this level. For example, some variables with little effect upon overall annual yield could have a significant influence on half-hourly or seasonal yield and hence on export to grid. It is therefore reasonable to argue that greater realism could be instilled into such models and ratings if, without compromising their essential simplicity, the LZC performance algorithms could be modified to include the most significant of these effects. To achieve this, a principled approach to model variable selection was devised and applied to the LZC problem, and is described in this chapter.

To generate the data against which to fit a statistical model, the half-hourly LZC models were run repeatedly with input variables selected at random. The extremes of each input variable, e.g. location, were set according to the possible boundary cases in the UK; in the case of LZC specifications the boundary values of products currently available on the market were selected. A statistical model was built for each LZC technology using best subsets analysis. This method is used in removing variables that have the least significant effect on the outcome, and selecting the best statistical model from a range of candidates. The benefit of this approach is that the hourly models are treated consistently and that additional LZC types can be represented quite easily using this methodology.

The sizing of an exporting LZC technology compared to demand may have an influence on the proportion of generated electricity that is used in the home and that which is exported. This can be important in calculating the monetary cost of import and export. Further statistical models of the proportion of electricity export relative to supply and demand were derived from the data. Correlating input variables to export becomes more significant when CO_2 emissions are considered. The time-dependence of CO_2 per unit of electricity through the day and year and the cumulative effect of export timing can lead to a significant difference between the technologies effectiveness in displacing CO_2. As well as the statistical analysis of each of the models, an analysis of the behaviour of the models in combination was made so that any effects of combining LZC types could be reflected in the models.

8.2 Deriving Statistical Models

The statistical method followed to build the models is the same for each technology. The procedures used are presented below. The data was generated using at least 500 runs of each LZC model. The values of the independent variables were selected at random from within the chosen boundaries in the case of climate variables and from existing databases in the case of equipment specifications. The statistics plug-in PHStat for Excel was used to automate parts of the statistical analysis (Levine, 2005). Stepwise regression was performed upon each LZC model, followed by a best subsets analysis to confirm that the best model was found.

With stepwise regression, a model is built systematically from the variables that are considered most significant, while avoiding analysis of all alternative models. The variables are chosen in order of the p-value (the chance that the correlation between the variable and the result is due to random error). The forward stepwise method was used, where variables can either be added or removed from the model if it improves the final fit. The significance level of p-value<0.05 was then used to determine whether each variable should be added to the model or not.

For best subsets analysis a fixed procedure is used, as given in Levine (2005). The steps are to choose the independent variables and fit a full regression model so that the Variance Inflationary Factor (VIF) for each variable can be found. The Variance Inflationary Factor is defined as:

$$VIF_j = \frac{1}{1 - R_j^2} \quad \text{(Equation 8.1)}$$

Where

VIF_j is the Variance Inflationary Factor for variable j
R^2_j is the coefficient of multiple determination of Xj with all other X variables

Any variables with a VIF>5 are likely to be highly correlated with other independent variables, and the variable with the highest VIF can be removed from consideration. A best subsets regression will produce a list of all potential combinations of independent variables. The Cp statistic measures the difference between a fitted regression model and a true model. Those models that have a Cp close to or less than k+1 (where k is the number of explanatory variables) can be regarded as statistically significant. From these the model that best describes the behaviour of the LZC can be chosen. A complete analysis of the model then describes the match of the statistical model to the original half hourly one. All the input variables to the full models were chosen as independent variables.

8.3 Solar Water Heating Models

For solar water heating, a simplified design method model already exists in the UK (Kenna, 1984). However, a further simplified representation has been used in HERs for the UK for some time, implying that the calculations involved in the Kenna model are too complex for use in a DEM. A half hourly model from Duffie and Beckman (1994) was analysed to estimate how it performed. The response of each model to the variation in variables was noted, and where variables had little influence in the results they were held static in a new model. A statistical model was then derived for use in a DEM.

8.3.1 Duffie and Beckman Method

An energy balance equation as given in Duffie and Beckman (1991) and shown in equation 4.8 was used for each half hour of the year, modelling seasonal and daily variations in energy yield. The Duffie and Beckman model is of the physical processes leading to annual yields. This means that the yield at specific times can be given depending upon the profiled input data that is available. Variables in this instance change both seasonally and through the day. The input variables are given in Table 8.1. The collector specifications were chosen at random from the SPF collector database (Institut für Solartechnik SPF, 2006).

Variable	*Description*
Collector Area	The aperture area in m^2. This was taken to be up to $4m^2$.
Collector Azimuth	The collector is pointed with respect to due south in this direction. The best performance is at 0°, due south to get the maximum irradiation. The boundary values were assumed as -45° (SW) to 45° (SE).
Collector Tilt	This is normally about 35° in the UK but a tilt equal to the latitude is optimal. This was assumed to vary from zero to 60°.
External temperature days	The mean external temperature for the day in °C. This was replicated from BS5918 temperature data.
F_R	The Collector Heat Removal Factor. This gives the ratio of actual efficiency to the maximum possible.
Hourly Hot Water Load	This is the mean hot water load for each half hour, depending upon the demand temperature and volume.
Hourly Irradiation	This is the daily profile of irradiation upon the collector surface. For each half hour, the mean irradiation is quoted. This varies by latitude, azimuth, and tilt.
Latitude	The position north or south of the equator, measured in degrees. This value is between 55° and 62° north in the UK.
Room temperature	According to standard occupancy heating, the indoor demand temperature is 21°C. For this study, values between 16°C and 23°C were used.
Tank loss	This refers to the heat loss of the tank in W/m^2 surface area.
Tank Size	The size of the preheat storage tank in litres. This was estimated at 100-200L.
Temperature of Water	The temperature of the supplied water in °C. This can be replicated from the BS5918 method.
U_L	Overall heat transfer coefficient in $W/m^2/°C$

Table 8.1: Variables for the Duffie and Beckman Method and their description

The correlation coefficients of the variables to output are given in Table 8.2. The variables with significant correlations to the results are shaded.

Variable	*Correlation Coefficient against Results*
Ambient Temperature	0.0932
Azimuth	0.0306
Collector Area	0.7388
F_R	0.1723
Irradiation	0.287
Latitude	-0.0821
Hot Water Demand	0.0649
Room Temperature	0.0207
Tank Loss	0.0364
Tank Size	0.0032
Tilt	-0.2064
U_L	-0.4777

Table 8.2: Duffie and Beckman correlation of variables to results

8.3.2 Stepwise Regression of Solar Water Heating Model

The variables for the most detailed model are latitude, azimuth, tilt, collector area, F_R, U_L, tank size, tank loss, room temperature, demand temperature, hot water demand, irradiation, and temperature. Note that variables with high Variance Inflation Factors (VIFs) were removed from consideration to avoid collinearity of the explanatory variables. Latitude and temperature had VIFs in the region of 30, and this is logical given that the monthly temperature is directly related to latitude. Latitude was removed as a variable as temperature can be derived directly from degree day region. A stepwise regression and best-subsets regression were performed and eight models had a Cp close to or less than the criteria k+1. The results of the stepwise regression are given in Table 8.3.

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-1977.676	148.086	-13.355	0.000	-2268.631	-1686.721
Collector Area	546.704	11.085	49.318	0.000	524.924	568.484
F_R	1396.940	117.190	11.920	0.000	1166.689	1627.191
U_L	-303.531	11.393	-26.641	0.000	-325.916	-281.146
Irradiation	0.065	0.004	17.947	0.000	0.057	0.072

Table 8.3: Duffie and Beckman: Results of Stepwise Regression

8.3.3 Best Subsets Analysis of Solar Water Heating Model

In best subsets analysis, each combination of variables is analysed to determine the best model for the data. If more than one combination offers satisfactory results, the optimum model can be selected based upon criteria such as parsimony or analysis of the residuals. Best subsets analysis was then performed on the SDWH model. The variables are named according to the convention given in Table 8.4, and information about the alternative models is shown in Table 8.5.

Variable	*Naming Convention*
Collector Area	X1
FR	X2
UL	X3
Tank Size	X4
Tank Loss	X5
Demand	X6
Irradiation	X7

Table 8.4: Naming convention for variables in SDWH Best Subsets Analysis

Model	*Cp*	*k+1*	*R Square*	*Adj. R Square*	*Std. Error*
X1X2X3X4X5X6X7	8.000	8	0.880	0.878	294.723
X1X2X3X4X5X7	6.423	7	0.880	0.878	294.551
X1X2X3X4X6X7	6.903	7	0.880	0.878	294.694
X1X2X3X4X7	5.277	6	0.879	0.878	294.507
X1X2X3X5X6X7	6.061	7	0.880	0.878	294.442
X1X2X3X5X7	4.496	6	0.880	0.878	294.274
X1X2X3X6X7	4.903	6	0.880	0.878	294.395
X1X2X3X7	3.277	5	0.879	0.878	294.209

Table 8.5: Candidate Best Subsets for Duffie and Beckman model

The adjusted R^2 can be used for comparison – this figure is calculated accounting for the number of variables in the model. The Cp statistic measures the difference between a fitted regression model and a true model. When a regression model with k independent variables contains only random differences from a true model, the average value of Cp is k+1, the number of variables. Any model where the Cp statistic is equal to or below the k+1 figure can be considered, and there are 8 suitable models from the 126 combinations that are suitable. Note that the adjusted R^2 value is the same for each. The model X1X2X3X7 is the same as that derived from the stepwise regression. The variables in the model are Collector Area, F_R, U_L, and Irradiation. The equation that was formed for the SDWH output is given below.

$$Q_{SDWH} = -1.977 + 0.546Area + 1.396F_R$$
$$- 0.303U_L + 0.65I \qquad \text{(Equation 8.2)}$$

Where

Q_{SDWH} is the energy output of solar domestic water heating in MWh

Area is the collector area in m^2

F_R is the collector heat removal factor (0-1)

U_L is the overall heat transfer coefficient in $W/m^2/°C$

I is the incident irradiation in Wh

8.4 Photovoltaic Model

PV systems can be modelled using a similar set of variables to solar water heating. Although photovoltaic installations are not subject to tank losses and the thermal balance of the collector as with solar water heating, the performance is subject to the effects of temperature difference between the panels and the air around them and performance decreases as they heat up. Duffie and Beckman and the popular RETScreen modelling software package give similar half hourly versions of this calculation. Losses due to the inverter are typically expressed as a static factor rather than as a value that changes over time.

8.4.1 Half-Hourly Photovoltaic Calculation Method

The variables as used in the half-hourly PV calculation are given in Table 8.6.

Variable	*Description*
Area	The effective area of the solar cells in m^2.
Array Losses	The general losses associated with dirt or snow on the cells, expressed as a percentage.
Collector Azimuth	The collector is pointed with respect to due south in this direction. The best performance is at 0°, due south to get the maximum irradiation. The boundary values were assumed as -45° (SW) to 45° (SE).
Collector Tilt	This is normally about 35° in the UK but a tilt equal to the latitude is optimal. This was assumed to vary from zero to 60°.
Efficiency	The percentage of energy that can be converted to electricity, discounting the effects of heating in the cells.
Inverter Losses	The losses associated with converting the electricity generated from direct current to alternating current suitable for use on the grid, given as a percentage.
Latitude	The position north or south of the equator, measured in degrees. This value is between 55° and 62° north in the UK.
Power Conditioning Losses	The loss in performance associated with the balance of system equipment in the installation.
Temperature Coefficient	The loss in power associated with the heating of the solar cells. As the cells heat up, more energy is released to the environment rather than converted to electricity.

Table 8.6: Variables used in PV model and their description

The correlation coefficients with the results are given in Table 8.7. The variables with statistically significant correlations to the results are shaded.

Variable	*Correlation Coefficient with Results*
Area	0.3733
Array Losses	-0.183
Azimuth	0.0185
Efficiency	0.7671
Inverter Losses	0.0674
Latitude	0.0926
Power Conditioning Losses	-0.0339
Temperature Coefficient	0.0998
Tilt	0.0722

Table 8.7: Correlation of Half-Hourly Variables to Results

8.4.2 Stepwise Regression and Best Subsets Analysis of Photovoltaic Model

The variables for the most detailed photovoltaic model are latitude, azimuth, tilt, area, power conditioning losses, temperature coefficient, array losses, module efficiency, inverter losses, irradiation, and temperature.

The model was run 500 times with input variables selected at random within the chosen boundaries. Latitude has high VIF with temperature and is known to affect irradiation, so was removed. Inverter losses, power conditioning losses and array losses vary by the same degree (0-5%, RETScreen) and are multiplied with each other in the model. To reduce the variables to seven, the limit of that which can be meaningfully analysed in the software, these were specified together as a single variable in the model. Both stepwise regression and best subsets analysis show that the best way to represent the PV yield is to use all variables present in the model - Table 8.8.

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-3113.866	189.052	-16.471	0.000	-3489.285	-2738.447
Temperature Coefficient	30035.053	41780.466	0.719	0.474	-52932.588	113002.695
Area	108.992	4.115	26.486	0.000	100.821	117.164
Efficiency	7836.550	196.078	39.966	0.000	7447.178	8225.922
Latitude	-2.164	2.324	-0.931	0.354	-6.780	2.452
General Losses	1129.403	135.833	8.315	0.000	859.667	1399.140

Table 8.8: Overall Statistics for the PV Model

Figure 8.1 shows the results of the half hourly model versus the simplified model derived statistically.

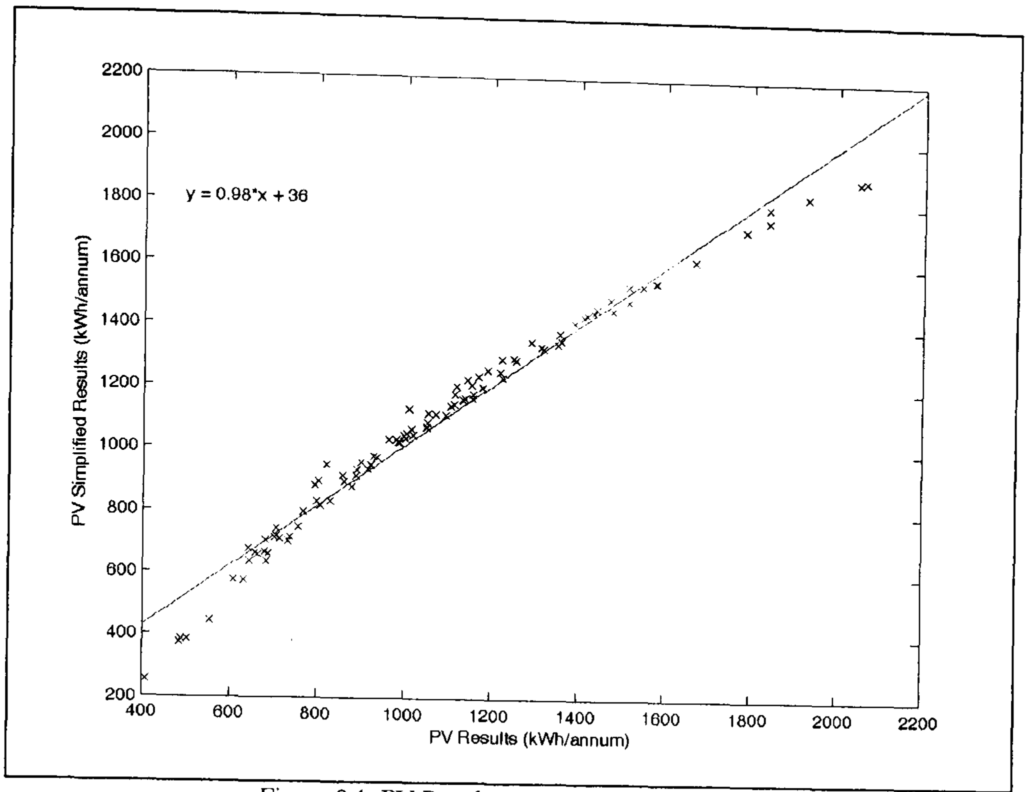


Figure 8.1: PV Results vs. Results of Simplified Model

$$Q_{PV} = -3.113 + 30.035C_{Temp} + 0.108A + 7.836Eff - 0.002L + 1.129Loss \qquad \text{(Equation 8.3)}$$

Where

Q_{PV} is the energy output of the PV system in MWh
C_{Temp} is the temperature coefficient of the PV panel in W/°C
A is the area of the PV panels in m^2
Eff is the efficiency of the PV panels as a %
L is the Latitude of the site in °N
Loss is the general losses associated with balance of system equipment as a %

8.5 μ-CHP Model

Combined heat and power in the home is generally designed to be heat led. The unit will typically be designed for continuous operation, with variable heat and electricity generation levels depending upon the demand for heating in the dwelling. Because design methods for μ-CHP are not yet widely available, a method has been created based upon the variables available amongst those collected for use in a HER.

8.5.1 μ-CHP Half Hourly Model

The inputs for the μ-CHP model and their descriptions are given in Table 8.9.

Variable	*Description*
Degree Day Region	The UK is divided into 21 degree-day regions within the BREDEM-12 document. Temperatures and irradiation change depending upon the degree-day region.
Specific Loss	The heat loss of the dwelling in W/m^2/°C, as given in the BREDEM-12 calculation.
Solar Gains	The daily solar gains admitted through the windows, as calculated in BREDEM-12.
Lights and Appliances Gains	The gains in Watts from lights and appliance use through the day. As calculated in BREDEM-12.
Cooking Gains	The gains from cooking, in Watts. As calculated in BREDEM-12.
Metabolic Gains	The gains from the occupants' body heat in Watts. As calculated in BREDEM-12.
Set point	The target indoor temperature of the dwelling.

Table 8.9: Variables used in μ-CHP model and their descriptions

A heating pattern based on standard occupancy is assumed. This means that the dwelling is heated for two periods, one of 2 hours in the morning and one of 7 hours in the evening. The calculation is performed for each month of the year and minute of the day.

$$Q_h = U_B\left(t_{sp} - t_a\right) - G_B \qquad \text{(Equation 8.4)}$$

Where

Q_h is heating input in Watts
U_B is the specific loss of the dwelling in W/m^{2}K
t_{sp} is the set point temperature in °C
t_a is ambient temperature in °C
G_B is incidental gains in Watts

If the timer is on, the thermal output is set to match or exceed the losses. Electrical output is set to be the equivalent setting to the thermal output. The correlation coefficients with the results are given in Table 8.10. The variables with statistically significant correlations to the results are shaded.

Variable	*Correlation Coefficient against Results*
Degree Day Region	-0.1464
Specific Loss	0.4272
Solar Gains	0.0551
Lights and Applications Gains	0.0178
Cooking gains	-0.0763
Metabolic gains	0.0014
Set point	0.7932

Table 8.10: μ-CHP Correlation of Variables to Results

8.5.2 Stepwise Regression of μ-CHP Model

The results of the stepwise regression exercise are given in Table 8.11.

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-81.771	3.178	-25.730	0.000	-88.015	-75.527
Set point	3.857	0.102	37.773	0.000	3.656	4.057
Specific losses	163.480	7.451	21.941	0.000	148.841	178.120
Degree day region	0.644	0.037	17.621	0.000	0.573	0.716
Solar gains	18.159	4.753	3.821	0.000	8.820	27.497

Table 8.11: μ-CHP Model suggested by stepwise regression

8.5.3 Best Subsets Analysis of μ-CHP Model

The variables for the most detailed model are degree-day region, specific losses, solar gains, lights and appliances gains, cooking gains, metabolic gains, and set point. The model was run 500 times with input variables selected at random from within the chosen boundaries. None of the variables was found to have a high VIF against the others. The naming convention for the variable is given in Table 8.12. The models suggested by best subsets analysis are given in Table 8.13. Figure 8.2 shows the chart of the simplified model versus the hourly one.

Variable	*Naming Convention*
Degree Day Region	X1
Specific Loss	X2
Solar Gains	X3
Lights and Appliances Gains	X4
Cooking Gains	X5
Metabolic Gains	X6
Set Point	X7

Table 8.12: Naming convention for variables in μ-CHP Best Subsets Analysis

Model	*Cp*	*k+1*	*R Square*	*Adj. R Square*	*Std. Error*
X1X2X3X7	2.3	5	0.813732	0.812226516	4.677678
X1X2X3X5X7	4.1	6	0.813807	0.811922781	4.681459
X1X2X3X6X7	4.2	6	0.813783	0.811897958	4.681768
X1X2X3X4X7	4.3	6	0.813734	0.81184897	4.682378
X1X2X3X5X6X7	6.0	7	0.81386	0.811594984	4.685537
X1X2X3X4X5X7	6.1	7	0.813811	0.811544583	4.686164
X1X2X3X4X6X7	6.2	7	0.813785	0.811518622	4.686487
X1X2X3X4X5X6X7	8.0	8	0.813863	0.811214945	4.69026

Table 8.13: μ-CHP Models Suggested by Best Subsets Analysis

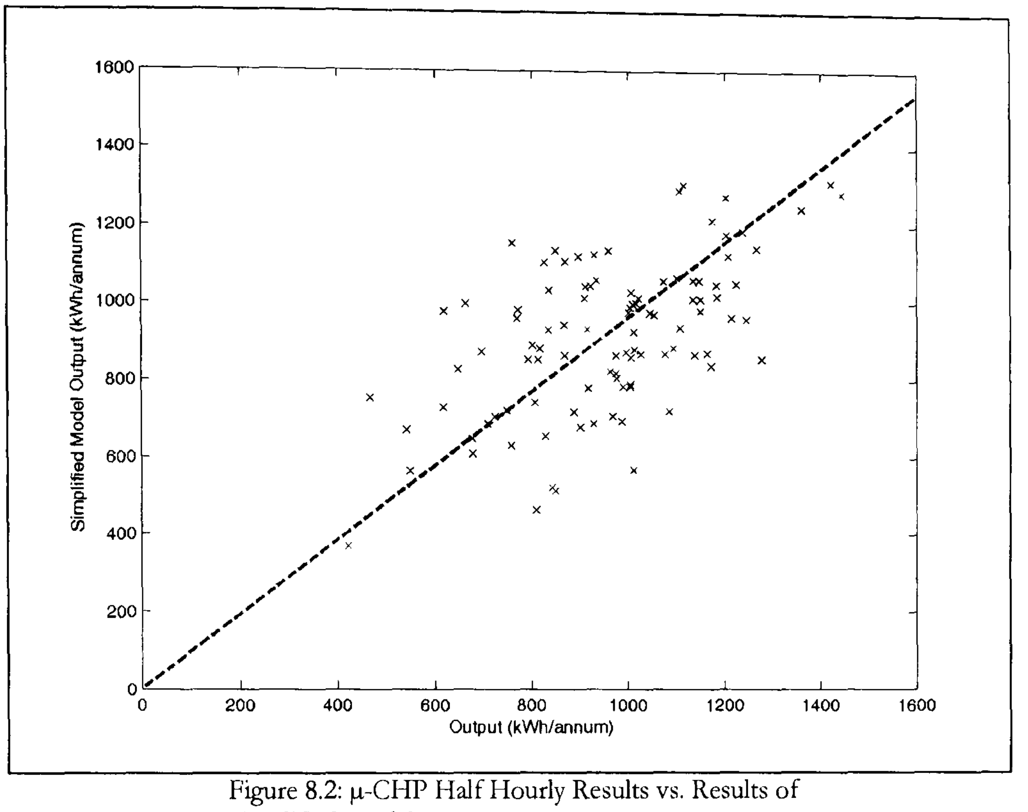


Figure 8.2: μ-CHP Half Hourly Results vs. Results of Simplified Model

$$Q_{E,\mu CHP} = -0.082 + 0.004T_{SP} + 0.163Loss + 0.001DDreg + 0.018G_{sol} \quad \text{(Equation 8.5)}$$

Where

$Q_{E,\mu\text{-}CHP}$ is the annual electrical output in MWh

T_{SP} is the set point in °C

Loss is the specific loss of the dwelling in W/m^2K

DDreg is the degree day region in which the dwelling is located (1-21)

G_{Sol} is the solar gains in kW

8.6 Demand Model

The model for domestic electricity demand is based upon a complex series of calculations, for which a roster of appliance ownership is input (Stokes, 2005). The results are given to a minute by minute resolution for each day of the year.

This is too computationally intensive to run many times as with the simple models, therefore twelve monthly mean days were calculated for each case.

8.6.1 *Inputs for the Demand Model*

The input variables for the demand model are given in Table 8.14.

Variable	*Use*
Built Form, Age, and Form Value	Used to determine the floor area of the dwelling from a rapid survey.
Floor Area	Floor area in m^2.
Number of Occupants	Number of people occupying the dwelling.
Income Number	Linked to expenditure on electricity
Social Number	
Heat	Whether electric storage space heating is used
Water	Whether water is heated using the immersion, and the type of heating: none, summer only or all year round.
Water Size	Size of the immersion heater: 1, 2, or 3 kW
Oven, Hob, Microwave, Kettle, Fridge, Freezer, Fridge Freezer, Washer Drier, Washing Machine, Tumble Drier, Dishwasher	Whether the item is present in the house and the number of items present in each case.

Table 8.14: Variables of the Demand Model and their use

The correlation coefficients of the variables to the resultant demand are given in Table 8.15. The variable with significant correlations to the results is shaded. Note that only occupancy has a strong statistical correlation to the overall annual demand.

Variable	*Correlation Coefficient*
Built Form	0.0189
Age	-0.0394
Form Value	0.0517
Floor Area	0.0199
Number of Occupants	0.7300
Income Number	0.0330
Social Number	0.0646
Water Marker	-0.0834
Water Size	-0.0213
Hob Marker	0.0297
Oven Marker	0.0538
Microwave Marker	0.0783
Fridge Freezer Number	0.0060
Fridge Marker	0.0090
Freezer Number	-0.0515
Washer Drier Marker	-0.0419
Washing Machine Marker	0.0306
Tumble Drier Marker	-0.0227
Dishwasher Marker	-0.0673

Table 8.15: Demand Model Variables and Correlation Coefficients

8.6.2 *Best Subsets Analysis of Demand Model*

The results of best subsets analysis are given in Table 8.16.

Best Subsets Analysis						
X2						
Regression Statistics						
Multiple R	0.868					
R Square	0.754					
Adjusted R Square	0.753					
Standard Error	431.672					
Observations	500.000					
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	1638.880	76.752	21.353	0.000	1488.082	1789.678
Num Occ	917.477	23.508	39.029	0.000	871.291	963.664

Table 8.16: Demand model suggested by best subsets analysis

The algorithm that was ultimately derived for electrical demand is:

$$D_E = 1.64 + 0.92Occ \qquad \text{(Equation 8.6)}$$

Where

D_E is the electrical demand in MWh

Occ is the number of occupants

8.7 Export Correlations

The relative sizing and the type of LZC can affect how much of the output is used in the home and how much is exported; moreover it can affect the timing of the export and therefore its effectiveness in displacing CO_2 emissions. A particular combination of LZCs could offer a distinctive export profile compared to single technology systems. The proportion of output exported can be estimated according to the key variables of the LZC models as derived from statistical simplifications. The export can be expressed in statistical terms just as the overall output can.

Tests were run with PV and μ-CHP as examples to determine their respective outputs and expected export. An important influence in this is that PV produces most of its output at midday, whereas μ-CHP tends to produce more in the morning and evening. Export is lower when demand is higher, so both of these output profiles must be judged in relation to the electricity demand profile. This was the course of action taken in these studies. The variables used in the derivation of the model for PV export were: temperature coefficient, area, efficiency, latitude, general losses, and demand. The variables used in the derivation of the model for μ-CHP export were: degree day region, specific loss, solar gains, cooking gains, set point, and demand. The results are shown in Table 8.17 and Table 8.18 below, using the same naming conventions as before for each technology. From these results an equation was used to describe the performance of the LZCs in terms of export in general.

Model	*Cp*	*k+1*	*R Square*	*Adj. R Square*	*Std. Error*
X2X3X4X5X6	6.799613	6	0.672189	0.668871395	85.84504
X1X2X3X4X5X6	7	7	0.673382	0.66940651	85.77565

Table 8.17: PV export: best subsets suggestions for simple model

Model	*Cp*	*k+1*	*R Square*	*Adj. R Square*	*Std. Error*
X1X2X3X5X6	5.81704	6	0.509361	0.504395187	343.2691
X1X2X5X6	6.002825	5	0.507189	0.503207142	343.6803
X1X2X4X5X6	6.702625	6	0.508481	0.503506396	343.5768
X1X2X3X4X5X6	7	7	0.510173	0.504211564	343.3327

Table 8.18: μ-CHP export: best subsets suggestions for simple model

The equation describing PV export is:

$$E_{PV} = -0.25 + 36.42C_{Temp} + 0.04A + 2.99Eff$$
$$-0.009L + 0.515Loss - 0.06Demand \quad \text{(Equation 8.7)}$$

Where

E_{PV} is the export of the PV system in MWh
C_{Temp} is the temperature coefficient of the PV panel in W/°C
A is the area of the PV panels in m²
Eff is the efficiency of the PV panels as a %
L is the Latitude of the site in °N
Loss is the general losses associated with balance of system equipment as a %
Demand is the electrical demand in the household in MWh

And the equation describing μ-CHP export is:

$$Q_{E,\mu CHP} = 0.52 + 0.08T_{SP} + 0.001Loss$$
$$+0.025DDreg - 0.52G_{sol} - 0.285Demand \quad \text{(Equation 8.8)}$$

Where:

$Q_{E,\mu\text{-CHP}}$ is the annual electrical export in MWh
T_{SP} is the set point in °C
Loss is the specific loss of the dwelling in W/m²K
DDreg is the number of the degree day region in which the dwelling is located (1-21)
G_{Sol} is the solar gains in kW
Demand is the electrical demand in the household in MWh

8.7.1 CO_2 Displacing Efficiency of Export

The profile of kg CO_2/kWh of electricity is characterised by having low values in the early morning, with morning and evening peaks, the greater peak being in the evening. The winter demand is more markedly profiled compared to the shallow and low summer profile. To displace maximum CO_2, μ-CHP should be set to switch off in the morning – but this is usually when it is most needed for space heating. Conversely, PV exports most at midday and during the summer, meaning that the kg CO_2/kWh is always close to the average annual figure. In general, the profile of μ-CHP output as generated by the half hourly model conforms to the expectation that it will displace more CO_2. The results of the study are shown in Table 8.19.

	Average	*Maximum*	*Minimum*
Emissions for PV Export kg	67.36	462.41	0
Emissions for μ-CHP Export kg	510.01	1097.7	24.6
PV Export kWh	150.04	1031.5	0
μ-CHP Export kWh	1386.35	2969.1	87.03
kg CO_2/kWh PV	0.45	0.48	0.4
kg CO_2/kWh μ-CHP	0.36	0.39	0.28

Table 8.19: Comparison of PV export vs. μ-CHP export: kg CO_2/kWh

The split of export from electricity consumed in the home is primarily for billing reasons. Although all output effectively displaces CO_2, the quantity attributable directly to consumption in the house and that which is used by the grid can be distinguished. This becomes more important in the context of a HER where a homeowner may be recompensed in greater measure for direct usage than for export, or vice versa.

8.7.2 Export from Combinations of LZCs

When LZCs are installed in combination, there may be interactions between their specifications that mean that more or less electricity is exported than if they were standalone installations. Although this effect can be seen when using a half-hourly calculation, it remains to be seen when calculating energy yields on the yearly scale. Five hundred runs of an example combination, PV and μ-CHP, were performed to measure potential interactions between the explanatory variables. Those variables that were selected for the statistical models for PV, μ-CHP, and demand were used as explanatory variables for export. These were analysed together for connection to the proportion of electricity exported from the dwelling over the year. The model, with an adjusted R^2 of 0.91 against the results of the half hourly models is:

$$Q_{E,Combined} = -1379 + 0.76PV + 17.62DDreg + 2.86Loss + 66.34T_{SP} + 0.53\mu CHP - 158Occ - 0.38Demand$$
(Equation 8.9)

Where:

$Q_{E,Combined}$ is the combined export in MWh
PV is the PV Output for the year in MWh
μ-CHP is the μ-CHP Output for the year in MWh
T_{SP} is the set point temperature in °C
Loss is the specific loss of the dwelling in W/m²K
DDreg is the degree day region in which the dwelling is located (1-21)
Demand is the electrical demand in the household for the year in MWh
Occ is the number of occupants

8.8 Chapter Summary

Half hourly models commonly used in predesign analysis of LZC systems can be unsuitable for use in HERs. In this chapter, an approach has been proposed to simplify the representation of such models. The objective of this part of the research was to replicate the information given by the half hourly models using a statistical model of the correlation between the input variables and the results.

The choice of boundary values for the variables needs to be made in order to generate data from which to derive statistical models. The selection of ranges of variables for each technology was made in accordance with the usual range encountered in the use of design methods, as given in previous chapters. To simplify the models and express them as statistical correlations between the most necessary variables and the outputs, a standard regression procedure was used. Initially stepwise regression was used to find a model. A best subsets approach was then used to compare against the previous approach, along with prior knowledge of which variables were most likely to be easily obtainable in a home energy survey.

The proportion of output not used in the dwelling but exported to grid is also of importance in a HER. Estimation of this figure was made by the same means of statistical simplification as the overall output figures. The profiles of output and export have characteristics likely to change the quantity of CO_2 emissions they displace. This characteristic was quantified using the same statistical approach as the other simplification exercises, and can be used to give guidance on the relative effectiveness of each LZC in displacing CO_2. Combinations of LZC technologies could become more common in the future as methods of reducing the carbon footprint of a dwelling. Just as the production profile of each technology has an effect upon output and export profile and therefore the emissions displaced by them, so a combined export profile changes depending upon the relative sizing of the technologies. This too has been expressed using simplified equations derived from regression analysis.

CHAPTER 9: CONCLUSIONS AND FURTHER WORK

9.1 Discussion

The main aim of the research described in this thesis was to develop and test a methodology for representing LZCs at the appropriate level of detail for typical HER software. Accordingly, statistically derived models relying on simplified design methods were considered broadly appropriate. However, it was also apparent that some potentially significant factors in LZC energy production needed to be reflected in the final equations. Additionally, it was clear that the conventional cost-based HER methodologies did not reflect some complex interrelationships introduced by LZCs. As these factors and relationships are likely to impact seriously on CO_2 mitigation strategies, it was essential to develop a methodology to account for them and to give full credit for well-designed systems. How to resolve the intricate conflicts and subtle tradeoffs necessary to achieve this aim was a research question that demanded investigation and reflection on different levels, involving implementation and testing of candidate models, and inquiry into the nature of HERs and the complexities of deregulated energy markets.

Submodels of BREDEM-12 have been proposed to support comparison of LZCs. These draw upon the data tables provided with BREDEM-12 where possible, to ensure consistency within the model. The climate data provided by BREDEM-12 has been expanded and extrapolated to the half hourly level for midmonth days. Radiation profiles upon the tilted surfaces expected of collectors were generated from BREDEM-12 data using a version of the Muneer algorithm coded especially for the study. The need for improved representation of the timing of energy flows within a dwelling has been identified and a suitable lighting and appliances demand profile generator has been evaluated, adapted, and applied to the energy rating domain.

Simplified models for three key technologies were derived from pre-existing design methods. These more complex hourly calculations model the physical processes occurring within the system for each time step. It was expected that the availability of irradiation would be the main factor in the performance of a SDWH system. Although the storage of energy as heat and the pattern of consumption of hot water by the occupants had a substantial effect on the day to day efficiency of the system, on an annual basis the effects were not so clear. They were described in the simplified model by the average reduction in efficiency following these effects. Therefore, the specifications of the collector had the major effect upon annual yield and could best be used in the HER model.

Although the performance of a PV system is affected by ambient heat, the irradiation received is the major influence. Other elements of the system can be covered by simple factors describing their efficiency. The derivation of these factors, left to the judgement of the user in most PV design methods, was made using measured data specific to the UK, to derive a model specific to the performance of UK PV systems. The findings of that study related to inverter sizing were used in this study to create an estimation of how inverter under sizing affected performance.

There was a requirement for a new model for μ-CHP at a level suitable for energy ratings. From specifications of μ-CHP units expected to arrive on the market, the unit's expected behaviour was coded in software and applied to an example dwelling modelled using BREDEM-12. Hourly profiles for space heating requirements are difficult to determine with accuracy short of a detailed simulation program. A simplified energy balance method was used to give a profile of what the space heating requirements might be through the day, considering some key elements like the specific loss of the dwelling. Elements of the CIBSE transmittance method were used in this derivation. Patterns in heating demand through the day and season could be identified from this basic method and were assumed as a guideline to electricity production by the unit. Comparison with measured data showed overall agreement. The output from the μ-CHP model confirmed that electricity export from this technology matches the national demand distribution relatively closely, confirming the claim that μ-CHP is particularly suited to smoothing out the peaks in electricity load from the domestic sector.

An alternative metric was used to deal with the perceived inconsistency of rating LZC export given the differing tariffs and subsidies assigned to particular installations. The CO_2 emissions displaced by export annually were used to compare the exporting LZC types on a more physical basis. To express the time-dependency of CO_2 emissions per unit of electricity, a half hourly profile of national CO_2 emissions due to electricity generation was created. This allows for comparison of the export profile of each LZC to estimate the quantity of emissions associated with electricity generation it can displace. This can be expressed either as a sum of emissions or as a factor describing the fit of the export to the profile of emissions. It was of importance to the study that the emissions metric was simple and transparently derived. The profile was derived for this study from freely available data about national electricity consumption and the generation mix at key times in the year.

The energy output of PV panels and μ-CHP were calculated for key dates and multiplied with the CO_2 emissions intensity figures for each half hour. The results were compared to evaluate the overall efficiency in terms of replacement energy and export. It was found that although a comparison based on profiles produced distinct differences for specific seasons, the annual result could readily be approximated by multiplying with a static emissions figure. However, under a profile based calculation, μ-CHP yielded higher than the average calculation, where PV panels gave a lower yield than average. The difference between the two yields in this instance was substantial, at 10%. This showed that the timing of export from LZC types significantly affects the net energy yield and should be considered in energy calculations, even if the significance may not always be visible to the end user.

LZC technologies may increasingly be installed in combination in the future in order to reduce the carbon footprint of each dwelling as much as possible. However the performance of each technology when used together side by side is not clear and may lead to more low paid export rather than displacing more electricity used in the home. An example combination of PV and μ-CHP was modelled against the demand profile of a single dwelling and the resulting average annual export and domestic displacement was taken. A simple equation was derived to describe the split in export and import under varying sizes of LZCs in combination.

The design method models were coded in software and run using a variety of assumed conditions. An approach using both stepwise regression and best subsets was used to determine the effect of each input variable upon annual yield, to remove the less significant variables, and to form simple equations with the remaining ones, representing energy yield for the year. These results varied in their fidelity to the original – in some cases a description of the model using fewer variables gave a significantly lower correlation with the results of the half hourly design method approach. It was confirmed that one of the major influences on LZC performance is the local climate, and that this should be considered of importance in a LZC energy calculation, at any level of complexity.

The solution to the problem of representing LZC in HERs led to the application of new approaches in deriving the methodology. The need for a general but transparent estimate of national electricity generation mix and CO_2 emissions drove the creation of a hypothetical 'best export profile' against which calculated data could be compared. Comparison of the export profile of LZCs against this profile can be described as a single factor, allowing for explicit evaluation of the performance of these technologies in light of the behaviour required of them. Parametric studies were performed in the course of simplifying the models, giving an ordered list of the influences upon LZC yield and also the potential yield of combinations of LZCs. As well as fulfilling the original goals, additional information has been gathered and created which is of benefit to the field of energy ratings and LZC technologies.

9.2 Limitations

The profile of CO_2 emissions per kWh was derived as an enquiry into the differing export profiles of LZCs in section 7.3. One criterion for the profile was that it was transparently derived and not subject to complex simulation. The reason for this was for it to serve as a consistent and easily understood basis for comparison of LZC export profiles. From this profile, a figure for typical CO_2 displaced per kWh was derived for each LZC. An approach more similar to simulation would have yielded results closer to the real output over the profile, but a general profile was called for in this case. Using the CO_2 emissions profile is a general means of comparison and although the results give a better representation of instantaneous CO_2 displacement they do not reflect reality exactly.

The CO_2 emission displacement of μ-CHP depends upon the heating patterns and is not fixed, as would be expected of PV. It can be tailored for best usefulness economically or in terms of emissions, as well as efficiency in space heating. Rather than attempting to predict what control strategy might be used in a μ-CHP unit, the approach taken in this instance is to assume a generic heating pattern of a dwelling, as opposed to one modified for best export.

9.3 Contributions

The detailed studies of three example LZC technologies have fully revealed the complexities underlying the aims of the thesis. Significant effects have been identified that impact on the potential of these and similar technologies for CO_2 reduction. Solutions have been obtained that enable these effects to be represented at a level of detail consistent with typical UK HERs as represented by the BREDEM-based NHER. The broad aims have therefore been achieved and the detailed contributions will now be presented.

Submodels within the DEM that need to be updated to support a LZC model have been identified and appropriate submodels have been obtained or derived for this. A satisfactory way of representing the immediate climate on a half hourly timescale has been derived. A study has been made of the half hourly output of models, allowing for evaluation of yield and export from the point of view of a profile generated by a model. This has been achieved based upon the limited input data that would be available to a HER. A clear process for selection and simplification of the models has been defined and used throughout. Attention has been paid to maintaining consistency with the data that exists within BREDEM-12. This process can be used in development of models for other LZCs. It has been shown that some models need to be more complex to capture this inherent aspect of representing LZCs. The variables that cannot be simplified or subsumed into calculations have been shown. A novel approach to comparing LZC performance and export in the context of HERs has been proposed and tested. The differences between LZCs attributable to their generation profiles have been outlined.

The use of CO_2 emissions as a basis for comparing the performance of LZCs has been based upon providing an alternative to the monetary costs, as these could prove to be changeable in the future. The CO_2 emissions metric could be used in addition to the traditional monetary basis for a rating or could provide the foundation for the rating itself. However, HERs must reflect the prevailing policy of the government. CO_2 emissions are only being advocated as a metric for home energy efficiency in the absence of clear guidelines on energy tariffs. Should it become more beneficial to present ratings based upon the monetary cost of energy then this should be used.

9.4 Further Work

The CO_2 kg/kWh displacement as derived in this study is quoted net of energy embodied in the generation and infrastructure, although losses due to transmission are covered. A future model could deal with the embodied energy of LZC technologies to calculate the energy payback times of the technologies. A few additions to the model would need to be made to achieve this. μ-CHP carbon displacement covers the electricity production and export only. A truer picture of μ-CHP carbon displacement might be gained by including the balance of the fuel consumed by the unit as well. Not being an exporting technology, SDWH was only analysed in terms of energy output, although this could also be achieved in terms of CO_2 emissions displacement of the fuel used. Using these features to calculate an energy payback as well as a financial payback time would increase the applicability and usefulness of the work.

The climate data used in this study was based upon twenty year averages. A domestic energy model may need to cope with comparatively rapid climate change and to incorporate this into the methodology. A methodology to adjust climate data based upon both historical data and predicted trends may become a requirement in future.

The study was conducted using measured data from existing installations and validated models for LZC systems. However, the installed base of LZCs is comparatively small at present. The typical characteristics of some LZC installations cannot be defined until identifiable trends in the industry emerge. The publishing of further measured data after field trials would also give a better picture of the performance of LZCs in practice. It is anticipated that obtaining knowledge of typical product specifications could lead to more streamlined and succinct models of LZCs that were typical of UK conditions. Conversely, as new μ-CHP products reach the market, identifiable product types could exhibit distinct production profiles that could be represented within a HER.

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APPENDIX A STANDARD DWELLING TYPES

A.1 Introduction

BEPAC technical note 90/2 gives details of standard dwellings for modelling and simulation. These can also be used in energy rating exercises using the National Home Energy Rating. We take aspects of the building fabric from the results and use them in an hourly energy balance. Specific loss and gains are the results of interest in this use of the calculation.

The dwelling categories covered by the BEPAC document are: detached house, semi-detached house, bungalow, post-1919 terrace, period terrace, and timber framed house. These were typical of the UK building stock in 1990. Detailed descriptions of construction and occupancy are given in the document but simplifications are made for entry into energy rating software.

The main reason for using standard dwelling type specifications is to use an agreed standard for specifying the dwellings themselves. It must be noted that use of the type specifications does not imply greater accuracy as measurements will be curtailed for use in an energy rating system.

The general form and specification of each dwelling type is detailed here, as well as the specific loss calculated for each dwelling. In all cases, the dwellings are situated in the London area. Unless stated otherwise, all dwellings are assumed here to face north at the front and south at the rear, where large patio windows would be placed to take advantage of thermal gains.

Details as to heating system and regimen are not given in the dwelling specifications. Specific loss pertains to building fabric only so the heating system is not of critical importance. However, the completed rating serves as a benchmark against which improvements to the dwelling fabric (such as μ-CHP) can be compared. Electrical consumption is also affected by a number of these factors. A number of further assumptions have been made in rating the dwellings. All buildings are assumed to have the same properties in this respect.

Buildings have gas heating with a post 1998 non-condensing boiler, a gas cooker, no passive vents and a standard extractor fan in the kitchen and bathroom. All chimneys are assumed to be blocked. TRVs are fitted to 50% of the radiators in the rooms.

A.2 Detached House

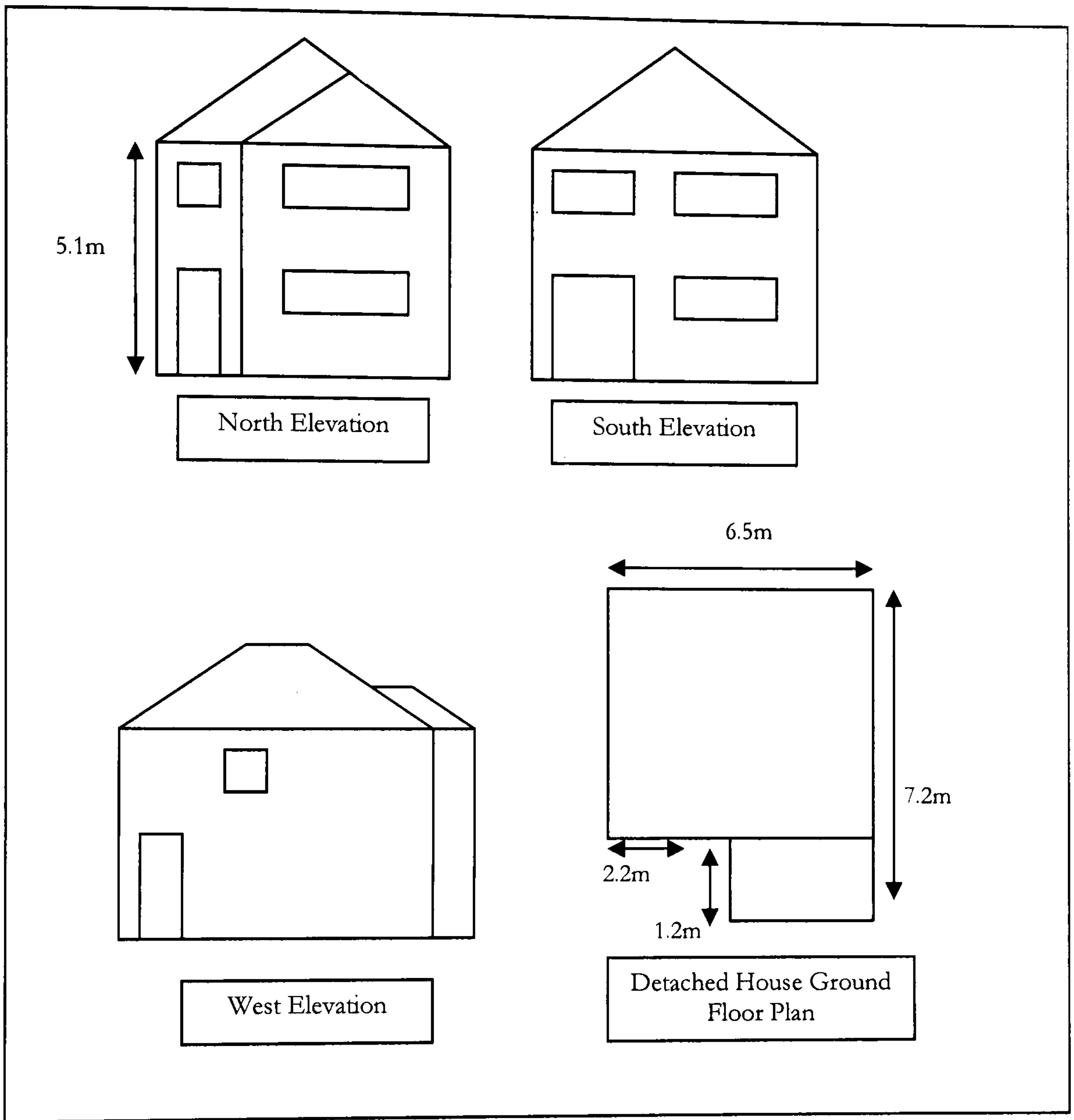

Figure A.1: Detached House Plans

Detached houses vary widely in their form. The size chosen for the BEPAC example has the average floor area of all the detached houses in the English House Condition Survey 1981.

Windows are timber framed single glazed. Doors are half single glazed timber frame. External walls are unfilled cavity throughout. The roof is insulated with 100mm of glass fibre quit.

Assuming gas central heating, the SAP rating is approximately 50. The EHCS of 2001 (EHCS, 2001) showed that 36% of dwellings had cavity wall insulation as opposed to 21% in 1996. For this study, cavity wall insulation was assumed as it would reflect the average. With 35mm mineral wool battens, the SAP increases to 60, the average rating for insulated cavity wall dwellings in 2001.

The specific loss calculated with the NHER rating software is 515.1 W/°C for the uninsulated case. With the insulation, it becomes 386.6 W/°C.

A.3 Semi-Detached House

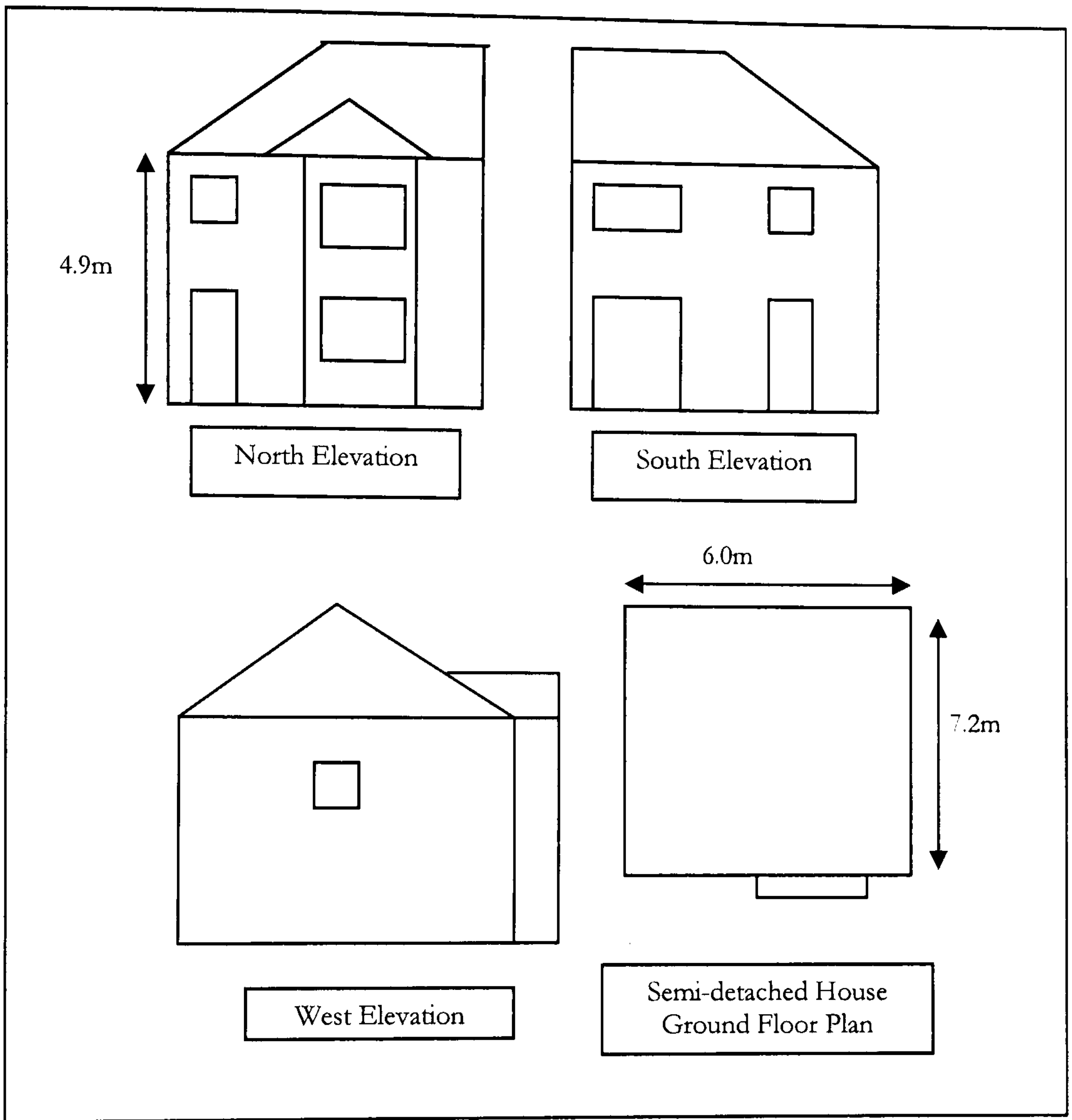

Figure A.2: Semi-detached House Plans

Semi-detached houses vary little in their form with age. The house type is a typical post 1919 semi-detached, with uninsulated cavity walls, a solid ground floor, single glazing and loft insulation. The specific loss is 266.7 W/°C, and the SAP rating is 71, NHER 7.3.

A.4 Bungalow

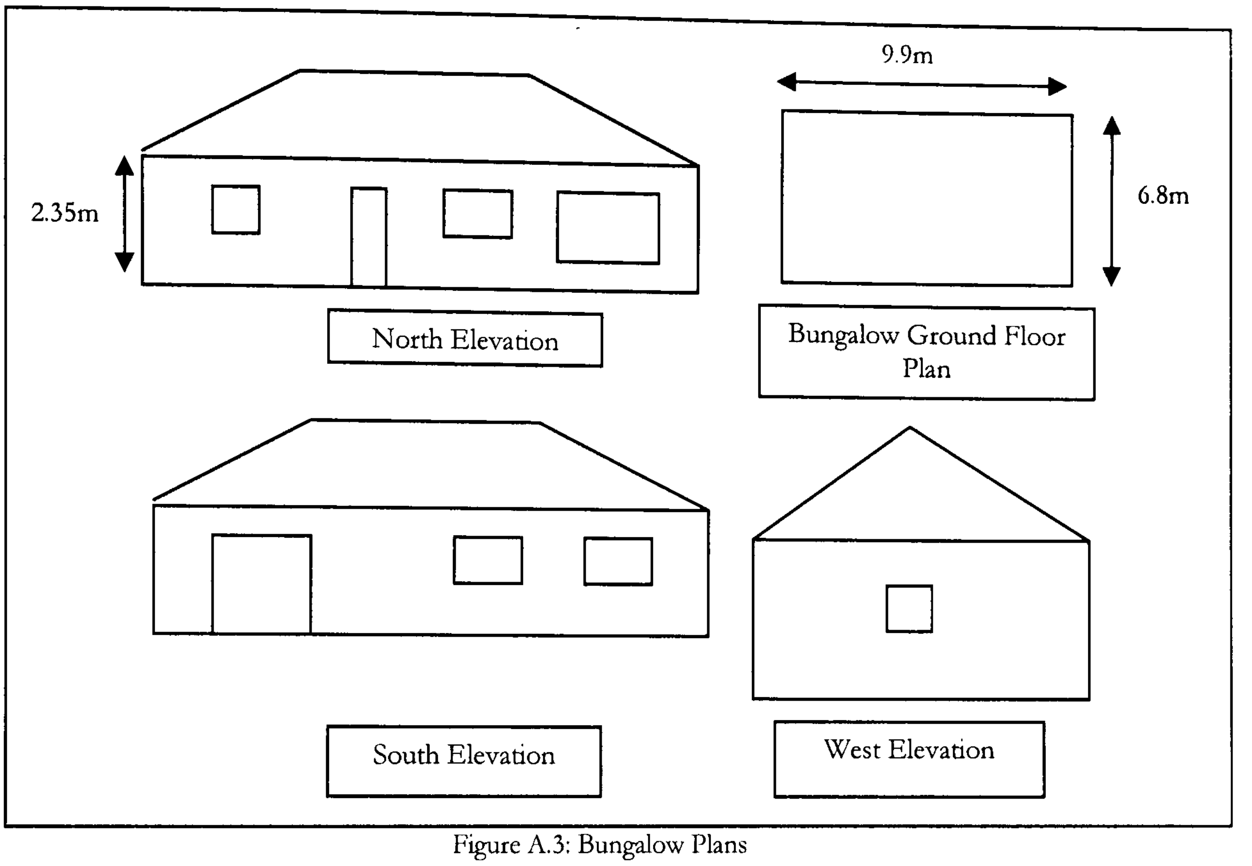

Figure A.3: Bungalow Plans

Although bungalows are similar in their form, the floor area varies. The example in the BEPAC document has the average floor area of all those on the records of the Nationwide building society. The bungalow has uninsulated cavity walls, single glazing and loft insulation, giving a specific loss of 252.0 W/°C. The SAP is 61 and the NHER is 6.1.

A.5 Post-1919 Terrace

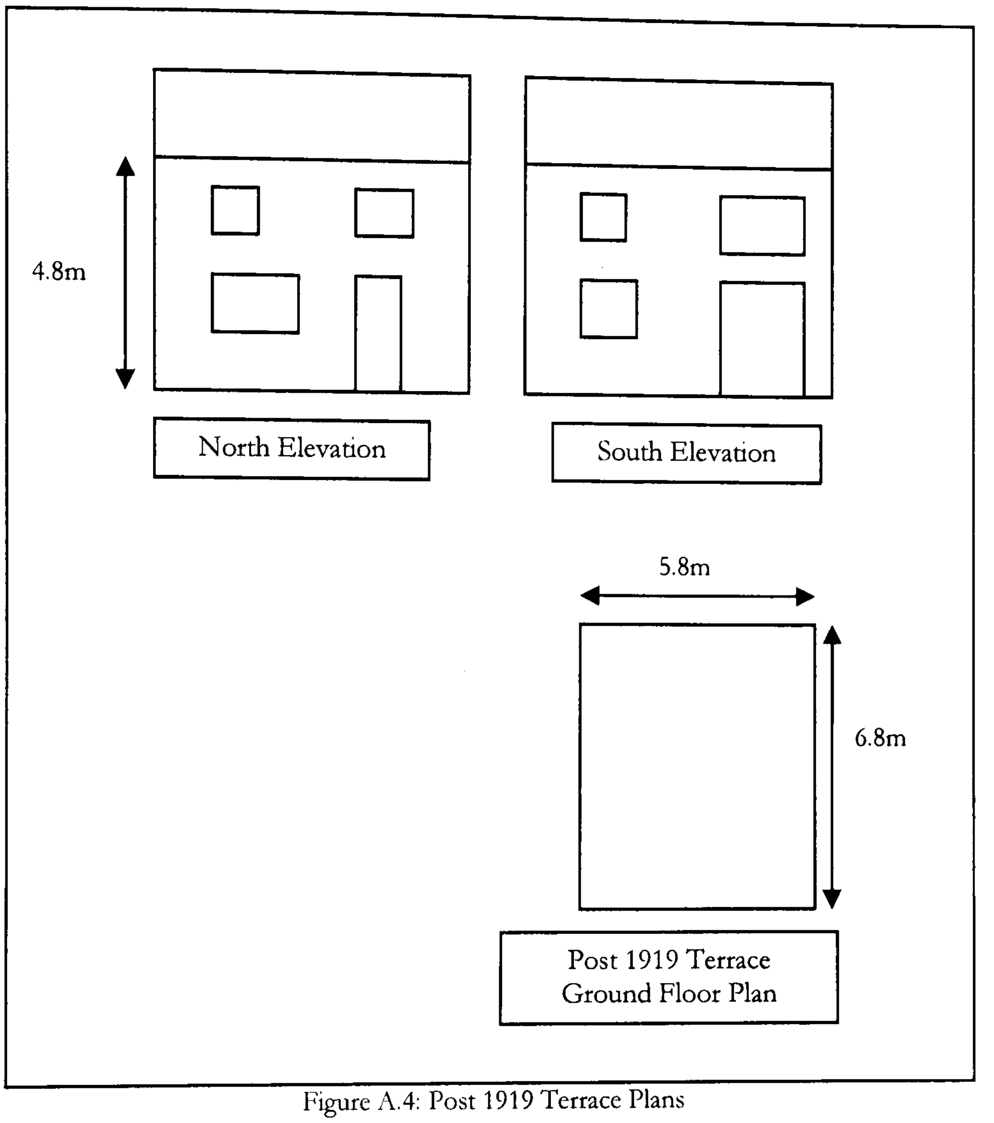

Figure A.4: Post 1919 Terrace Plans

The post 1919 terrace is based upon the national average dimensions for terraced houses. It has single glazing and loft insulation. The specific loss is 167.9 W/°C. The SAP is 82 and the NHER is 8.1.

A.6 Period Terrace

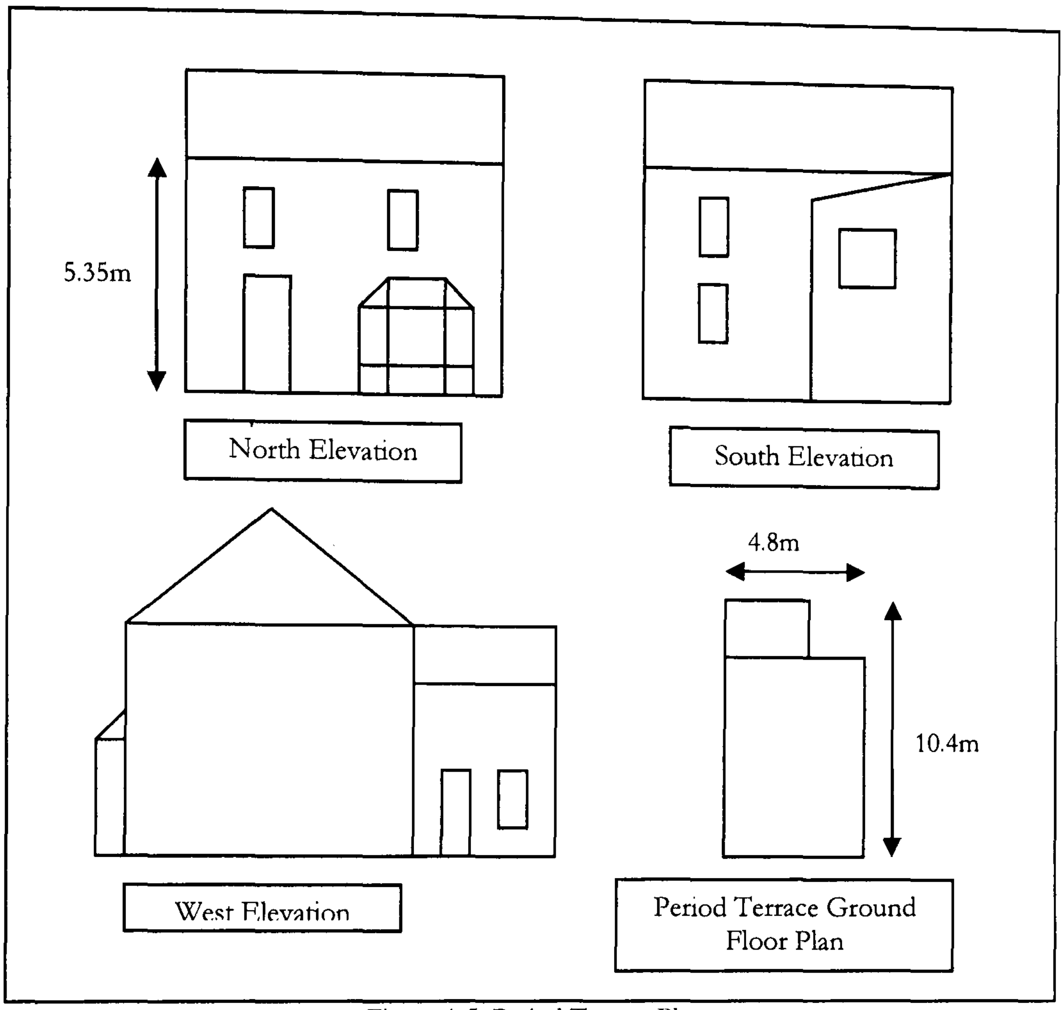

Figure A.5: Period Terrace Plan

Typically, period terrace houses have a rear extension, as is modelled in this case. The dimensions of the house are based on the national average for pre-1919 terraces. Both the main dwelling and the extension have solid brick walls, but the floor of the main dwelling is suspended timber and the floor of the extension is solid. The specific loss for this dwelling is 265.6 W/°C. The SAP is 61 and the NHER is 6.8.

A.7 Timber Framed House

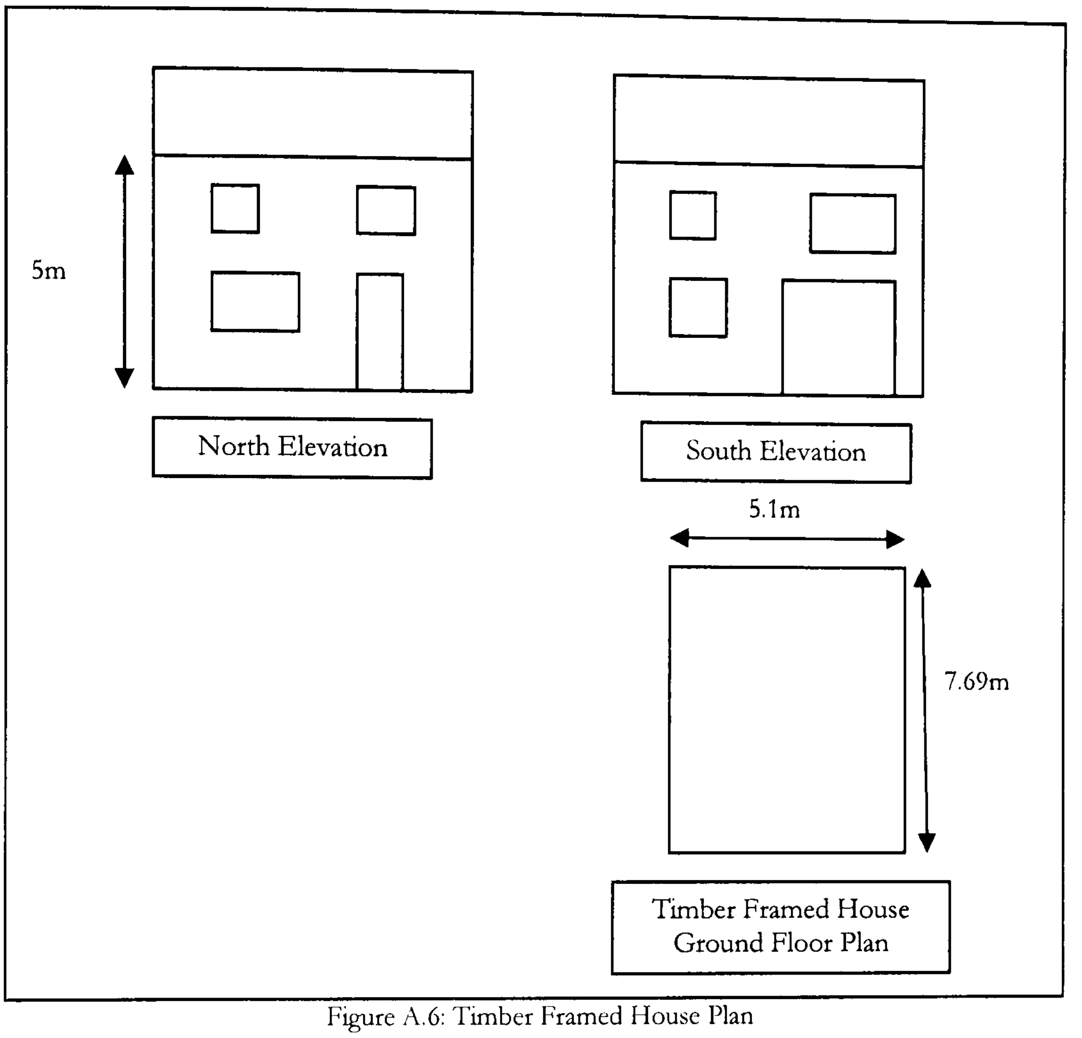

Figure A.6: Timber Framed House Plan

Specifications for a typical timber framed house are given. It has wall and loft insulation, and single glazed windows. The specific loss for this dwelling is 185.2 W/°C. SAP is 74, NHER is 7.5.